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An undersea reactor siting guide.

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An Undersea Reactor Siting Guide

Robert Neal Endebrock

The Pennsylvania State University

The Graduate School

Department of Nuclear Engineering

An Undersea Reactor Siting Guide

A Thesis in

Nuclear Engineering

by

Robert Neal Endebrock
))

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of the requirements
for the degree of

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Approved:

_____   _____
                             Assistant Professor of Nuclear Engineering
                             Thesis Advisor

_____   _____

                             Head of the Department of Nuclear Engineering

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ABSTRACT

This study deals with the evaluation of the consequences of the release of fission products from a nuclear reactor sited in the ocean. The ocean is divided into four distinct zones for which current velocity profiles and characteristic diffusion parameters are established. These zones are: Zone I (approximate depth of 50 meters or less) which is characterized by complete vertical mixing and tidal, estaurine, and wind induced currents up to one meter per second; Zone II (50 to 200 meters deep) which has as a major feature a thermocline located at one-half the depth, below which currents up to one meter per second may exist; Zone III (200 to 2000 meters) which consists of an upper mixed layer and a deep ocean layer separated by a thermocline at a maximum depth of 200 meters; Zone IV (greater than 2000 meters) which consists of four current layers with bottom currents as high as 10 centimeters per second.

A new fission product release inventory for undersea application is developed consisting of 100 percent of the soluble (including gaseous fission products) and one percent of the insoluble fission products or approximately 66 percent of the gross fission product inventory. Based on Carter and Okubo's diffusion model and with the assumptions of no current variance, zero mean vertical current velocity, and depletion of the inventory by radiological decay only, equations are presented which describe the physical transport and dispersion of the radioisotopes.

A computer program, SEADIF, is applicable to a person immersed in the water and is used to determine for both contained and un-contained systems the exclusion radius (a gamma dose less than 25 rem in the first four hours), the low population radius (less than 25 rem for an infinite time), and the gamma dose rate and radio-isotope concentrations as a function of time and position.

Biological uptake by the ecology leads to concentrations of certain radioisotopes in man's food chain in excess of maximum permissible concentrations. Results of an investigation of an instantaneous release from a 10 MW(t) reactor located in Ocean Zone II show that radioisotopes may exist in concentrations above permissible limits for as long as 2000 hours after release. A similar investigation of a continuous release from a 10 MW(t) reactor is carried out.

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CHAPTER 1

INTRODUCTION

A. Purpose

An eventual step in man's determination to explore the ocean
depths, whether for scientific, military, or industrial purposes, will
be the siting of nuclear reactor systems on the ocean floor. This step
can safely be taken only after a careful study has been made of the
possible consequences of an accidental release of fission products to
the ocean environment through a malfunction of the reactor plant.

The probability of a major accident in a land based reactor
plant is exceedingly small,[1] and it can be assumed that similar design
and construction practices will lead to equally remote possibilities
of an accident for a reactor sited in the ocean. As with reactors
sited on land, the major concern for undersea reactors is the release
of fission products to the environment. In this case, the environment
happens to be the sea instead of the atmosphere.

For reactors sited on land, it is necessary to investigate the
effects due to the direct radiation from both contained and airborne
fission products as well as the effect of the inhalation of the air-
borne radioactive contaminants.[2] In the seas, the problem is
considerably different. Because of the shielding effect of the water,
the direct radiation effects of a passing cloud of fission products
are more important than the direct radiation effects of the contained
fission products. The cloud of contamination is diffusing and moving
in a marine environment rather than an atmospheric environment.
Inhalation of radioisotopes is less likely. But the extremely complex

ecological realm that is interposed between the fission product release and man is most significant. In an area of fission product release, the ecology will, through biological uptake, concentrate radioactive nuclides in their systems, and in so doing, introduce the contamination into a primary link in man's food chain. The location of a reactor in an undersea environment introduces a number of potential hazards that must be considered.

B. Safeguard Considerations

    1. Direct Gamma Radiation. In the event of an accident, personnel in the vicinity of the fission product release may be exposed to direct gamma radiation. The primary concern is the direct gamma dose received from passage of the radioactive cloud which is diffusing in the water and being transported by the ocean currents. Because of the shielding effect of the water, the dose due to contained fission products is negligible.

    2. Ecological Contamination. Introduction of fission products into the ocean leads to contamination of the marine biota (flora and fauna). Fish may be exposed to the radioactive cloud, absorb and concentrate radioisotopes in their bodies, and then move considerable distances before being caught for eventual human consumption. Likewise, shellfish, seaweed, and other commercial ocean assets may become contaminated beyond limits acceptable for commercial users.

    3. Contamination of Vessels and Fishing Gear. Vessels passing through contaminated waters may introduce radioactive contamination throughout the ship's cooling and flushing water systems. In addition, the hull and other exposed portions of the vessel may become

contaminated. Fishing nets and trawling gear may become contaminated with subsequent potential exposure of members of the crew.

4. _Beach Contamination_. Ocean currents may carry the contamination many miles from the point of release. Contaminated waters could reach beach, island and coastal areas which are used for industrial purposes as well as recreational uses such as swimming, boating, or sport fishing.

5. _Bottom Deposition_. Contamination may settle out or precipitate to the bottom. Commercial dredging or mining operations could be affected, as well as the contamination of underwater cables which may subsequently be handled in the course of maintenance or repair.

The potential hazards of an accidental release are complicated by the fact that reactors may be sited in international waters, and the political as well as safety implications of any release will have to be considered.

In general, the contamination of vessels and fishing gear may be dealt with by post accident control of access to the affected waters. For this reason, it is important that current conditions may be accurately predicted from previous oceanographical surveys so that the extent of contamination may be estimated and all shipping warned of areas in which operations may be hazardous. Current monitoring will be required after an accident until surveys show that no radiological hazards exist.

Proper site selection would minimize beach contamination. Sites near shorelines should be selected only after extensive oceanographical surveys have indicated proper offshore current conditions

exist. An effort should be made to select sites so that minimum distances to the shoreline would exceed the distance to which concentrations in excess of allowable limits would extend.

The hazards in conjunction with bottom deposition are more easily handled. Again the key is accurately charting the course of travel of the contamination. Marine products harvested or mined from the bottom are not normally subject to major horizontal movement. Through post accident control, access to the marine products in an area of the ocean floor suspected of being contaminated could be temporarily suspended until samples had conclusively shown that any radiological contamination was less than permissible limits.

The direct gamma radiation hazard to man and contamination of the biota remain as the major problems. A reactor system may be the power source for life support facilities which implies that personnel will be in the vicinity of the reactor. How close may they be? How near may other facilities which house personnel be to the reactor complex? To what distances would it be necessary for personnel to be evacuated? From what area would it be necessary to restrict fishing or shipping? These questions have led to the following definitions applicable to ocean sites.

EXCLUSION RADIUS (SEA) is the minimum distance at which a person immersed in the water with a self contained breathing system would receive a total gamma radiation dose to the whole body not exceeding 25 rem in the first four hours following the accidental release of fission products.

LOW POPULATION RADIUS (SEA) is the minimum distance that an individual immersed in the water with a self contained breathing

apparatus could be located from the reactor such that he would receive not more than 25 rem total dose for an infinite period of time.

SAFETY RADIUS (SEA) is the maximum distance from the reactor that concentrations of radioisotopes in excess of maximum permissible limits in seawater may exist. The safety radius defines an ocean area in which fish would be suspect and contamination of vessels, fishing gear, and the ocean floor would be possible.

The choice of the whole body dose limitation of 25 rem referred to in the above definitions is based on the same philosophy as used in 10 CFR 20[3] and TID 14844[2]. This corresponds to the National Committee on Radiation Protection recommendations which state that a once in a lifetime dose of 25 rem need not be included in the determination of the radiation exposure status of a person.[4]

It may be well to consider the differences between the preceding definitions and the corresponding definitions for land based reactors (see TID 14844). Three such differences are particularly apparent.

(a) The time for the exclusion radius determination is set at four hours instead of two hours. This increase is due to the fact that it may require a greater amount of time to evacuate personnel from the ocean floor than from the vicinity of a land based reactor.

(b) No mention is made in regards to thyroid dose due to iodine. This concern is generated when the radioactivity is inhaled. As it has been assumed that all personnel have an air supply system independent of the environment and the reactor compartment, no possibility exists for inhalation of radioactivity.

(c)   Only direct gamma radiation from the passing cloud of radioactive material in solution is of consequence. The alpha and beta radiation is effectively shielded by the water.

It is the intent of this paper to present, within the framework of the preceding definitions, guidelines for evaluating the consequences of an accidental release of fission products to an ocean environment. In the next chapter, the ocean environment is examined and four idealized ocean zones are established. Conservative models of diffusion and dispersion are developed for these zones. In Chapter 3, the methods are presented for determining the maximum permissible concentrations of radioisotopes in seawater. In Chapter 4, a fission product release inventory is postulated for two cases - a contained (continuous fission product release) and an un-contained (instantaneous release) reactor system. An appropriate diffusion model is selected and together with the assumptions specified in Chapter 5, mathematical models are developed to describe the results of the transport and diffusion of the radioisotopes.

Having specified the model and defined the limits, the results of calculations of the exclusion radius, low population radius, and safety radius for a 10 MW(t) reactor located on the ocean floor are presented in Chapter 6. Conclusions based upon these results and recommendations for future work are discussed in Chapter 7.

CHAPTER 2

THE OCEAN ENVIRONMENT

In order to determine safe distance factors for undersea
reactors, it is necessary to have an understanding of the nature of the
environment which will be the vehicle for the diffusion and transpor-
tation of any radioactive contamination that would be accidentally
released.

A. Topography

The ocean may be divided into several topographical regions.
The continental shelf accounts for about eight percent of the ocean
floor and extends from the coast to depths of about 200 meters with
an average slope of 0° 07' or about 12 meters per mile.[5,6] This
submarine terrace, which borders the continents, may extend to
distances greater than seven hundred miles as is the case of the Sahal
Shelf off Northern Australia or along the coast of Siberia in the
North Polar Sea, or it may be essentially non-existent as is the case
south of Miami. It has an average width of 70 nautical miles off the
East Coast of the United States and an average width of 40 nautical
miles worldwide.[6] The continental shelf breaks sharply at about the
200 meter depth.

Extending from this break to the ocean depths, at an average
slope of 4° 17' for the next 2000 meters of descent, is the
continental slope.[6] Throughout both the continental shelf and the
continental slope there is a prevalence of submarine canyons, some

equal to the Grand Canyon in size.[5] The origin of these broad floored, steep sided troughs has not been fully explained, although recent evidence indicates that high velocity turbidity currents could cause undersea erosion. The Monterrey Canyon off California is 1600 meters deep.[6]

The deep ocean floor consists of oceanic rises, the flat abyssal plains, and the mid-ocean ridges. The mid-ocean ridges are inter-connected to form a long, nearly continuous ocean mountain system that winds over the entire globe. It is interesting to note that over 50% of the earth's surface lies between -2240 meters and -5750 meters and that the mean depth of the sea is -3800 meters.[7]

Rising a minimum of 1000 meters above the deep ocean floor are numerous steep sloped underwater mountains or "seamounts." Many of these at one time rose above the surface of the ocean where they were subject to erosion by the waves. Subsequent subsidence beneath the ocean surface has resulted in flat-topped seamounts called "guyots." Seamounts are most prevalent in the Pacific Ocean area where over 1400 have thus far been discovered.[6] They occur in all the other oceans as well, but are not nearly so numerous. An interesting feature of sea-mounts is the surprising absence of sediments from their summits. Photographs have shown rock outcroppings with only small amounts of sediment. The bare rock surface and ripple marks in the sediment indicate strong currents on the order of 16 centimeters per second or more.[6]

Mid-ocean canyons are found in the abyssal plains. These canyons are generally shallow (approximately 200 meters deep), steep sided, flat floored depressions, one to five miles wide.[7] Distinct

from the submarine canyons are the deep ocean trenches which occur
along the base of about one-half of the continental slopes of the
world. These may be either V-shaped or have relatively narrow, flat
floors. Table 1 gives the relative magnitude of some of the world's
major known deep ocean trenches.

B. Currents

The oceans cover 70.8% of the earth's surface and contain about
331 million cubic miles of water, nearly all of which is in constant
motion. This motion ranges from near zero currents at great ocean
depths to velocities in excess of 150 centimeters per second (3 knots)
in the Gulf Stream. A vertical separation of a few meters can find
water masses moving in opposite directions. The currents which
dominate the circulation of the water in the oceans may be categorized
as (1) wind induced surface currents, (2) major ocean currents, and
(3) deep ocean currents.

Wind Induced Surface Currents.[7,9] The wind is the principle
current inducing force in the surface and near surface waters. Through
frictional drag at the wind-water interface, the surface water layer
is put into motion as is each successive layer of water by the layer
immediately above. Due to the slippage between the layers, the water
velocity will be greatest at the surface and will decrease exponentially
with depth. Because of the Coriolis force which results from the spin
of the earth on its axis, the current direction is deflected to the
right of the wind direction in the northern hemisphere and to the left
of the wind direction in the southern hemisphere.

As a consequence of the earth's rotation, the surface current is

TABLE 1. Depths of Deep-Sea Trenches (in meters)[8]

PACIFIC OCEAN

Marianas Trench (Challenger Deep), western Pacific	11,034
Tonga Trench, southwest Pacific	10,850
Kurile-Kamchatka Trench, northwest Pacific	10,543
Philippines Trench (Mindanao Trench), western Pacific	10,033
Kermadec Trench, southwest Pacific	10,000
Japan Trench (Idzu-Bonin Trench), western Pacific	9,803
North Solomons Trench, western Pacific	9,142
New Hebrides Trench, southwest Pacific	9,038
Yap Trench, western Pacific	8,602
Palau Trench, western Pacific	8,142
Peru-Chile Trench, southeast Pacific	8,057
Aleutian Trench, north Pacific	7,672
Nansei Shoto Trench, western Pacific	7,512
Middle America Trench, eastern Pacific	6,662

ATLANTIC OCEAN

Puerto Rico Trench, western Atlantic	9,202
South Sandwich Trench, southwest Atlantic	8,262

INDIAN OCEAN

Sunda Trench (Java Trench)	7,452

directed at an angle of 45° with respect to wind directions. With
increasing depth, this angle increases and at a certain depth the
current is directed exactly opposite to the surface. This depth is
known as the "depth of frictional influence." At this point, the
current velocity is approximately 1/23 of the value at the surface.
The depth of frictional influence is the approximate lower boundary of
the "surface layer" and is located approximately 50 meters below the
surface in the middle latitudes and at greater depths at locations
nearer the equator. A schematic vector representation of this current
distribution is a logarithmic spiral, known as the Ekman spiral, and
is shown in Figure 1.

In areas where the ocean depth exceeds the depth of frictional
influence, the effective mass transport of the water in the surface
layer is approximately at right angles to the wind direction.

Surface currents due entirely to wind effects rarely exceed 50
centimeters per second. For an average wind velocity of 10 meters
per second, the surface current is about 35 centimeters per second.
Theoretical determinations of the surface current for a known wind
velocity depend upon an effective eddy viscosity coefficient and
are therefore very difficult to perform.[7] Large scale measurements
have shown surface currents to be about 1/33 of the wind speed at a
height of 30 feet above the water.[9] However, when associated with
large scale ocean currents, surface currents may reach 100 centimeters
per second. An example of this is to be found in the equatorial
regions where strong steady trade winds exist.

Major Ocean Currents. The large permanent ocean currents are
all related to the density distribution of the oceans but are
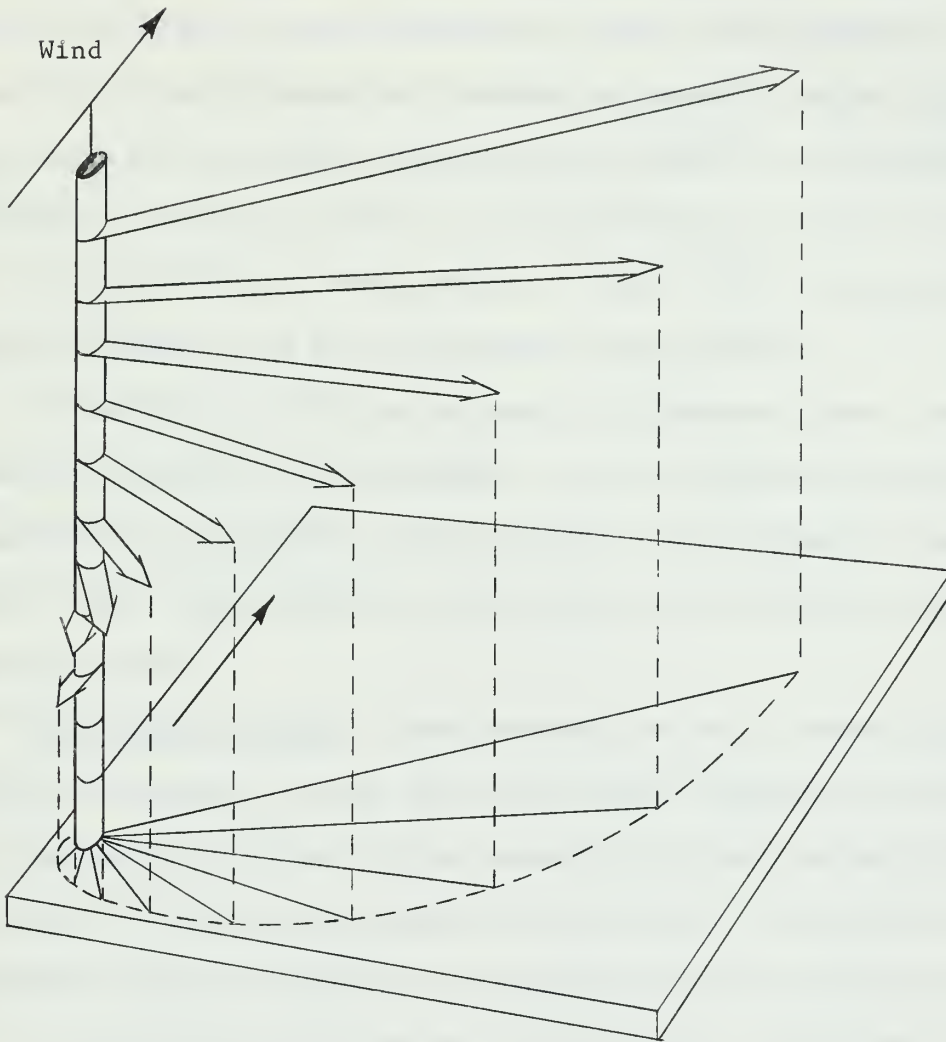
Figure 1. The Ekman Spiral. A schematic representation of wind induced currents. (Sverdrup[10])

maintained by the prevailing winds.[6] One dominant feature is the circular current motion in each of the major oceans - clockwise in the northern hemisphere and counterclockwise in the southern hemisphere. The center of this circular motion is offset due to the rotation of the earth.

These current systems can at best be described on an average

basis only. Seasonal, as well as day-to-day variations in extent, velocity, and direction can be expected. Major current systems such as the Gulf Stream or Equatorial Currents are actually narrow, swift ribbons separated by counter currents and are subject to considerable meanderings. Currents in excess of 100 centimeters per second may exist in association with these systems. Table 2 gives representative current velocities for a few of the major ocean currents.

In addition to the wind and density differences, these current systems are affected by the topography. The Gulf Stream, which is perhaps the most intensively studied current system, extends to depths of 1600 to 2000 meters along its eastern edge and is guided by the continental slope.[7]

Deep Ocean Currents. These currents are set in motion largely through the movements of cold, dense water which originates in the higher latitudes. This water sinks beneath the warmer surface waters and spreads out over the vast depths of the oceans. The Antarctic Intermediate Water and the Antarctic Bottom Water move northward at depths of approximately 1000 meters and 4000 meters, respectively. The Intermediate Water moves with a velocity of from six to nine centimeters per second whereas the average velocity of the Bottom Water is on the order of 0.5 to 1.0 centimeters per second. However, in some areas, particularly along the Western Atlantic Trough, velocities up to 25 centimeters per second for the Bottom Water have been observed. Similar sources of cold water exist in the Arctic, particularly in the Greenland Sea between Spitzbergen and Greenland.

An important layer of deep water movement in the Atlantic has

Table 2. Relative Magnitude of Major Ocean Currents

	Magnitude (cm/sec)	Depth (meters)
Atlantic Ocean		
Florida Current	80 – 180	600
Gulf Stream	150	500 – 2000
East Greenland Current	25 – 35	
Norwegian Current	30	
Straights of Gibraltar	100	
Equatorial Countercurrent	30	
Pacific Ocean		
Kuroshio	75 – 180	700 – 1400
California Current	15 – 30	500 – 1000
Cromwell Current	100 – 150	200 – 400
South Equatorial Current	50 – 65	
North Equatorial Current	25 – 50	
Pacific Equatorial Countercurrent	30 – 60	
Tidal Currents		
San Francisco Bay, maximum ebb	230	120
Bungo Straights		600
Akutan Pass, Aleutians, maximum ebb	70 – 450	

Note: Data for this table obtained from various sources (refs. 6, 7, 9, 10, 11, 12).

its origins in the Mediterranean Sea. Dense, saltier water moves out

of the Mediterranean Sea, over the Gibraltar sill, and spreads out at

an ever increasing depth. Similar intrusions of high salinity water

probably occur from the Red Sea and Persian Gulf to provide similar

sources of deep water movement in the Indian Ocean.[7]

Actual current measurements in the deep ocean are sparse but

generally range from 0.05 centimeters per second to 18 centimeters

per second. Deep water currents at the equator range from 3 to 12

centimeters per second.[7] Near Bermuda, measurements from 3 to 18

centimeters per second and higher have been recorded.[13]

Bottom currents were until very recently believed to be near

zero. However, such evidence as ripple marks and scouring effects

have been noted in photographs taken of the ocean floor at great

depths. These indicate significant bottom currents. Theoretical

calculations for the spreading of Antarctic Bottom Water give

results as high as 12 centimeters per second along the Western

Atlantic Trough.[7] A rule of thumb applied in the design of deep

sea moorings assigns a current of 10 centimeters per second at the

bottom.[13]

C. Vertical Mixing

In general, vertical mixing is limited to the surface layer.

Only in rare instances under the most severe storm conditions would

vertical mixing effects extend below 200 meters.

Immediately beneath the mixed surface layer is a zone called

the thermocline in which the sea water temperature decreases

rapidly resulting in a rapid density increase. The thermocline, or

pycnocline as it is sometimes called, separates the mixed surface

layer from the layers of intermediate and deep waters. Because of the

strong density gradient, the thermocline acts as an effective barrier

to vertical exchange. The thermocline is more pronounced and nearer

to the surface during summer months. With the cooling of the surface

waters in winter, it is lower and less distinct. As shown in Figure

2, the thermocline is less distinct at higher latitudes due to a more

even temperature and density distribution.
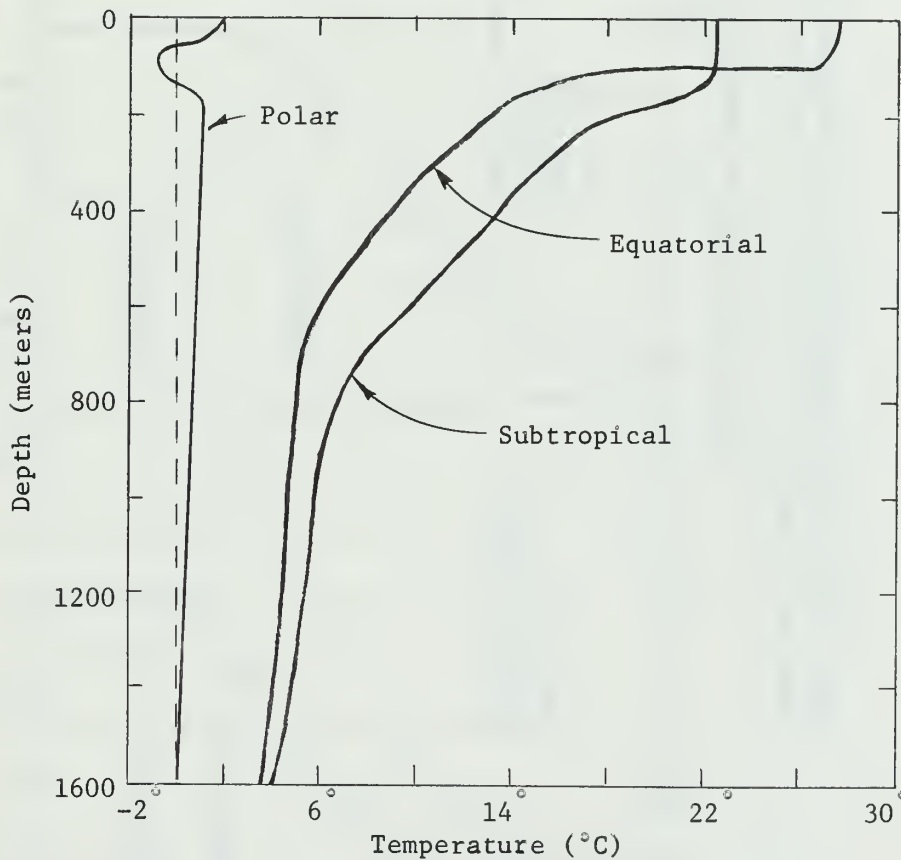
Figure 2. Major Types of Vertical Temperature Distributions
in the Atlantic Ocean (Neumann[7])

Figure 3 shows the clearly developed thermocline that exists

in the tropical and subtropical ocean areas. Figure 3 also shows the
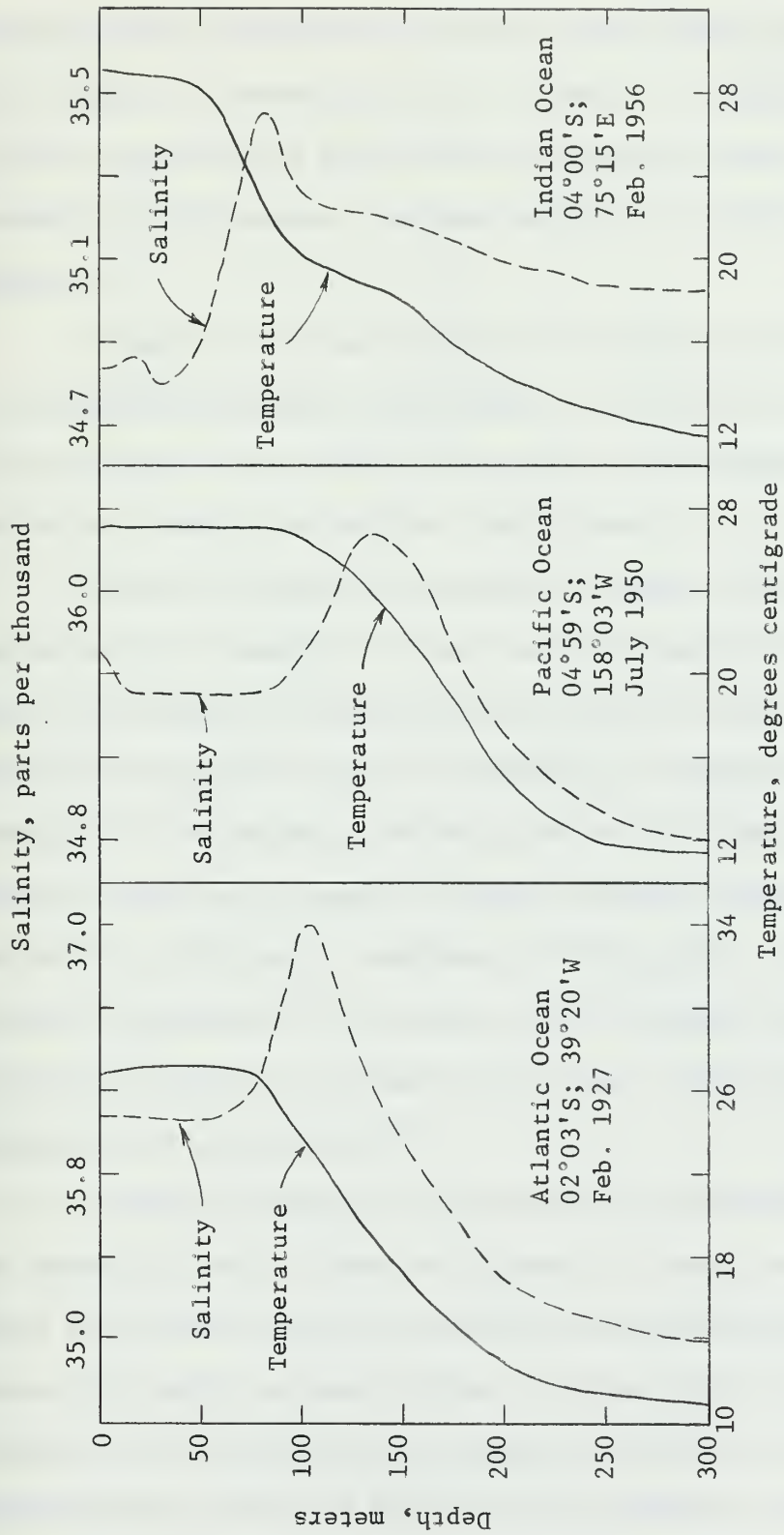
Figure 3.   Examples of temperature and salinity distribution with depth in the upper 300-meter layer of the tropical part of the oceans (Neumann7)

characteristic intermediate salinity maximum which occurs in the trop-
ical regions of converging surface currents. In these regions, sub-
surface currents carry high salinity subtropical water under the low
salinity tropical waters. Surface salinity is a minimum near the
equator.

Changes in surface temperature and wind conditions can lead
to an additional density discontinuity in the surface layer.
Stratification of the surface layer due to this additional thermocline
varies on a seasonal as well as a daily basis.

Since the density of sea water increases with depth, vertical
random motion is impeded. A mass that is brought to a higher level
will be surrounded by less dense water and will tend to sink back to
the level from which it came. Conversely, a water mass moving down-
ward will be surrounded by denser water and will tend to rise. This
stable stratification greatly reduces vertical turbulence although
its effect on horizontal turbulence is negligible. Artifical radio-
activity introduced at the surface moves vertically downward at a
velocity of about 0.1 centimeter per second. This motion ceases
abruptly at the thermocline.[13]

Vertical mixing may be increased by an ocean phenomenon known
as "upwelling" which occurs most commonly in areas near the coast
where the coastline lies to the left of the wind direction, or in
areas where major currents diverge. In these areas, there may be a
movement of the deeper waters towards the surface to replace the
surface waters which move away from the coastline or diverge because
of the current patterns. However, it is unlikely that these waters
would come from depths in excess of 200 to 300 meters. This phenomenon

is most conspicuous along the coasts of northwest and southwest Africa,
California, and Peru where the prevailing winds blow parallel to the
coasts and because of the Coriolis effect, the lighter surface waters
are blown offshore.[10] Upwelling due to major current divergence is
most common in equatorial regions.

D. Site Categorization of the Oceans

In order to quantitatively study the dispersion of fission
products in this complex environment, the ocean has been divided into
four, distinct, depth dependent zones for which current velocity
profiles have been established and characteristic diffusion parameters
may be determined. These idealized zones have particular value in
early site selection surveys when detailed oceanographical data for
a specific site is not available. They are generalized and must be
treated as such with every effort made to gain further information
from site investigation to adapt these zonal descriptions to more
nearly describe actual conditions. This is particularly true in
Zone I which includes the shallower ocean areas where local conditions
may vary a great deal. The velocity profiles associated with these
zones represent realistic maximums. Average velocity conditions are
as much as an order of magnitude lower.

Ocean Zone I (Depths on the order of 50 meters or less)

Although this zone is characterized by extremely complex
current patterns which may be influenced by tidal movements and
estuarine circulation, a uniform current velocity distribution on
the order of 100 centimeters per second has been established as shown
in Figure 4. Because the currents are dominately wind induced and
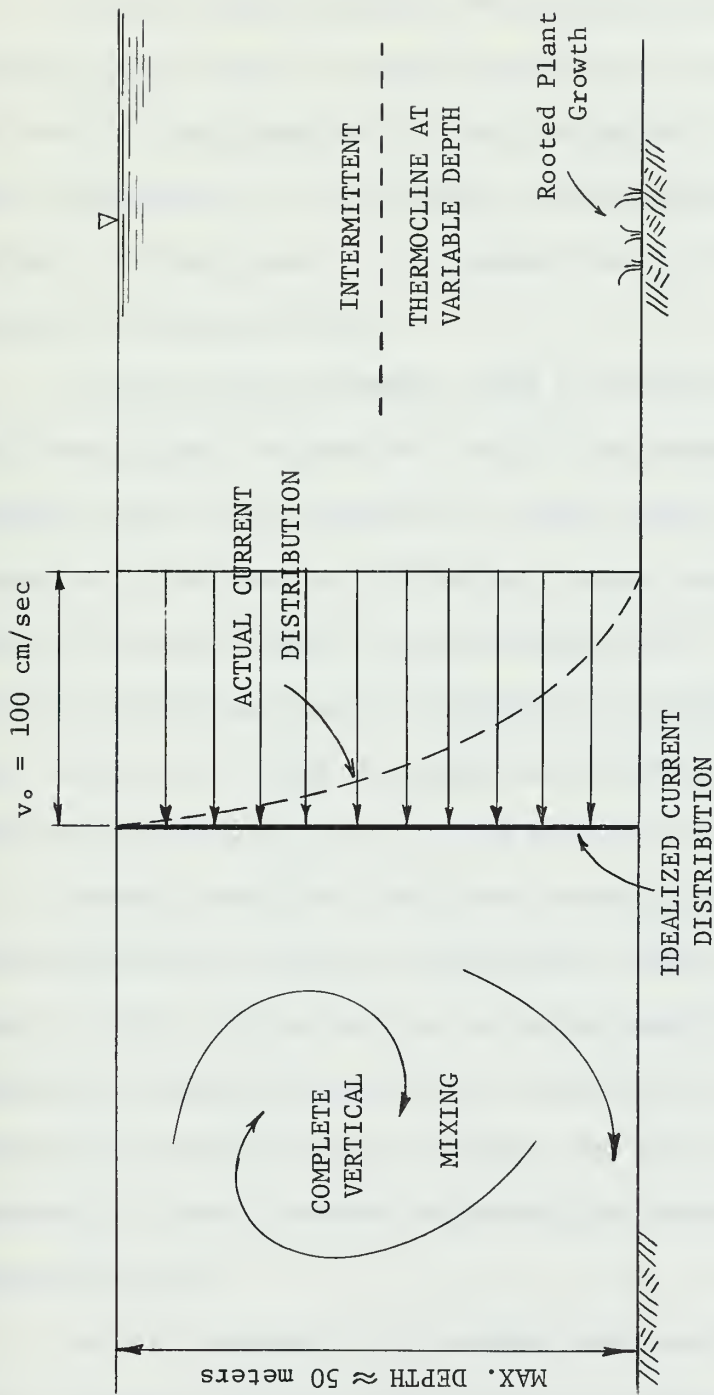
Figure 4.   Ocean Zone I (depth on the order of 50 meters or less)

the zone is subject to coastal upwelling, it is assumed that complete

vertical mixing exists throughout the entire depth.

In these shallow depths, the temperature distribution throughout

is more variable than is normally expected in the ocean. A thermocline

may exist at some depth but it would be subject to seasonal, if not

daily fluctuations. In the winter, the thermocline would be less

distinct. In any event, it is assumed that it is not an effective

barrier to vertical mixing.

At these shallow depths, light penetrates to the bottom to a

sufficient degree required for rooted plant growth. Because of the

abundant plant life throughout this depth, marine animals are

plentiful. This zone has the largest benthic population (flora and

fauna of the ocean floor) of the entire ocean.[5] And together with

the fact that these areas are generally the easiest ocean areas for

man to reach, both sport and commercial fishing are to be expected.

This zone covers approximately four percent of the ocean floor.

Certain areas fall into Zone I which because of local

conditions warrant special consideration. This includes consider-

ation of tidal fluctuations and estuarine conditions. Submarine

and coastal topography may define inland seas, sounds, gulfs, basins,

estuaries, harbors, fiords, straights, and other features for which

particular current patterns and descriptive oceanographical para-

meters may apply.

In fact, because of the complex nature of the current patterns

and the boundary effect of the submarine topography, application of

Zone I for siting purposes for nuclear reactors must be used

extremely judiciously. In particular, because of the vertical mixing

effect and the shallow depths, the effect of the surface boundary may have to be taken into account when applying the equations for determination of exclusion radius, low population radius, and the safety radius.

Ocean Zone II (50 to 200 meters deep). Zone II (Figure 5) corresponds generally to the continental shelf and although it consists of only four percent of the ocean floor, it is a region of high interest at this time. Because of the relative shallow depth of this zone, enough sunlight penetrates for floating plant life to exist at all levels so that marine life is abundant. However, it is unusual for rooted plant growth to exist even in the shallower regions of this zone. As is the case in Zone I, this area is easily accessible and is one of the most widely fished ocean areas.

The prominent feature of Zone II is the thermocline located at one half the depth which imposes an effective barrier to vertical mixing. Above the thermocline there is complete vertical mixing and high surface currents. These currents are wind induced. Beneath the thermocline currents are generally much less, but data is indeed meager. Due to the possibility of the influence of major current systems, a uniform current velocity distribution of 100 centimeters per second has been established. Currents on the order of 15 centimeters per second are more probable. An important point to remember, however, is that the direction of the current beneath the thermocline may be at any orientation to the surface currents (including opposite).

Vertical movement beneath the thermocline is assumed to be limited to diffusion and transfer by the ecology only since the mean vertical current is assumed to be zero.
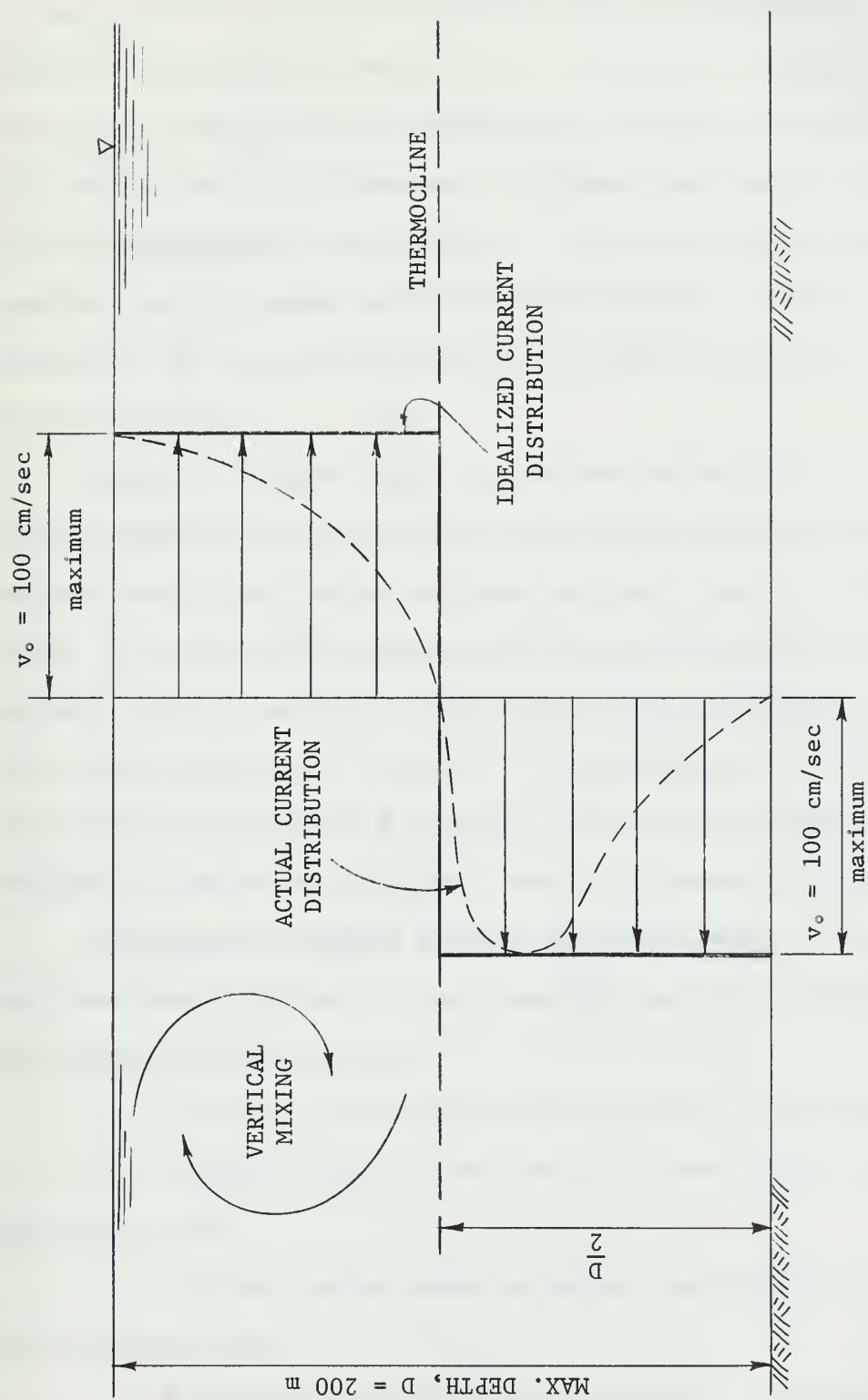
Figure 5. Ocean Zone II (50 to 200 meters)

Ocean Zone III (200 to 2000 meters deep). Zone III corresponds to the upper portion of the continental slope and comprises approximately 10 percent of the ocean area. It consists of an upper mixed layer and a deep ocean layer separated by a distinct thermocline at a maximum depth of 200 meters. The upper mixed layer is similar to the corresponding layer in Zone II. It is characterized by complete vertical mixing and wind induced currents. There is essentially no penetration of the lower boundary (thermocline) except by the marine life.

Beneath the mixed layer, the maximum currents may be as high as 150 centimeters per second in the area of major ocean currents. This maximum velocity will occur very near the lower boundary of the thermocline. The current will diminish with increasing depth until a zero velocity point is reached a short distance from the bottom. Beneath this, bottom currents on the order of 15 centimeters per second or less flow in the opposite direction. In this region, vertical movement is limited to diffusion. Zone III is shown in Figure 6.

Ocean Zone IV (Depths greater than 2000 meters). Zone IV includes about 82 percent of the ocean floor and may be divided into four layers as shown in Figure 7.

1. The mixed surface layer which extends to 200 meters.

2. The major current strata extending from 200 meters to 1600 meters deep.

3. The deep current strata extending from 1600 meters to 2/3 the total depth.

4. The bottom current layer which extends to the ocean floor.

Layers (1) and (2) correspond closely to the layers of Zone III.
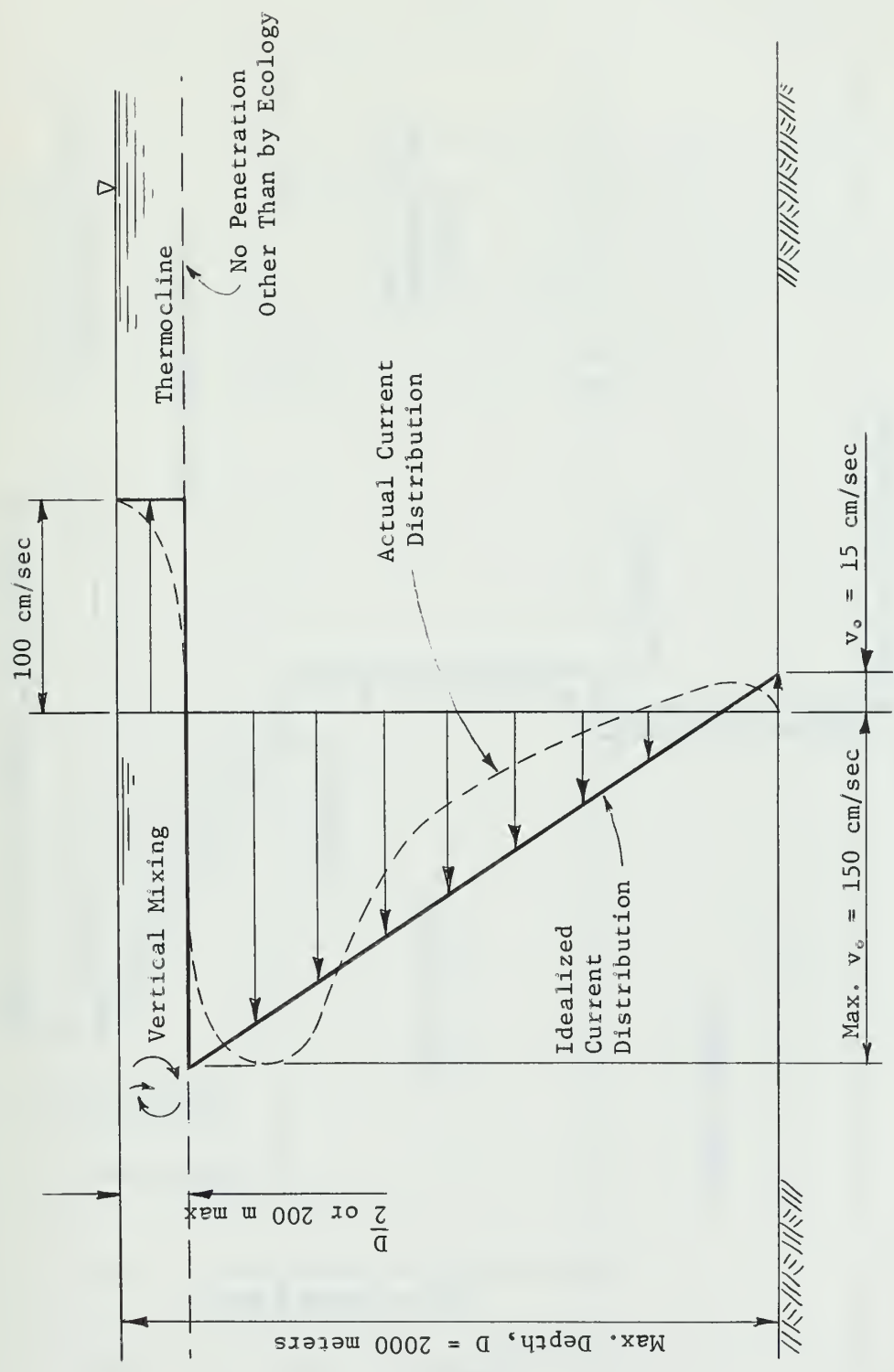
Figure 6. Ocean Zone III (200 to 2000 meters)
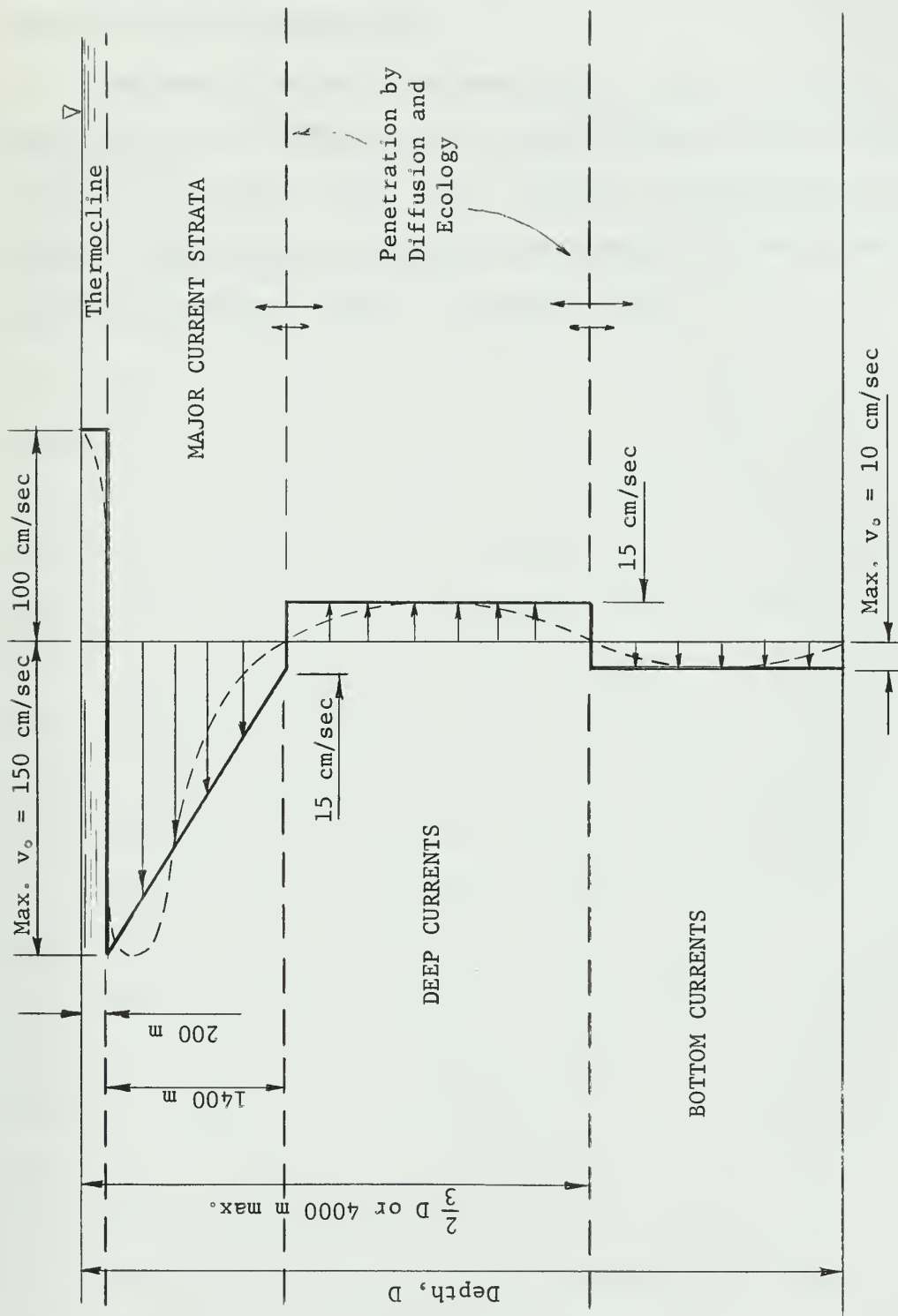
Figure 7. Ocean Zone IV (greater than 2000 meters)

The idealized current distribution in layer (2) runs uniformly from 150 centimeters per second at the thermocline to 15 centimeters per second at the 1600 meter mark.

The deep currents are represented by a uniform velocity distribution of 15 centimeters per second maximum, whereas the bottom currents are somewhat lower, with a maximum of 10 centimeters per second. Average deep ocean currents applicable to these layers are probably as much as an order of magnitude lower.

CHAPTER 3

DETERMINATION OF MAXIMUM PERMISSIBLE CONCENTRATION IN SEAWATER

One of the potential hazards most difficult to analyze is the contamination of the marine life. At present, the upper layers of the seas are the source of most fish taken by commercial fisheries and eventually consumed by humans. However, some species of food fish, although caught in the upper layers, are also found at great ocean depths. The commercially valuable sablefish has been found in waters 2000 meters deep. Other commercial organisms such as deep sea sole, cod, hake, squid, and shrimp are known to live or migrate into very deep waters at certain times in their life cycles.[14] Centers of fish populations undergo daily as well as seasonal vertical migrations. Many species live in water at depths of up to 2000 meters during the daytime but at night rise to within 200 meters of the surface. These migrants, perhaps only of limited commercial value in themselves, constitute a large part of the diet of many food fishes.

At the present time, fishing techniques and commercial markets make fishing at great ocean depths uneconomical. However, one species of red shrimp was commercially fished in 400 meters of water off Florida in the late 1950's.[8] Edible varieties of fish exist in abundance throughout the ocean depths and await only improved fishing techniques to be exploited for commercial consumption. This point is especially important as the world's population and food needs continue to increase. Acre for acre, the oceans are as fertile as the land,[8]

and the potential for development of huge food resources from the sea is vast.

Although human beings do not drink seawater directly in any great amount, they do consume many billions of pounds of seafood annually. For this reason, if no other, it is necessary to establish maximum permissible limits for radioisotopes in seawater. This determination of maximum permissible concentration of radioisotopes in seawater (MPCC) is complicated by the fact that the biota can concentrate certain isotopes within themselves to many times the concentration in the surrounding seawater. MPCC's have been determined by either the specific activity method or the concentration factor method depending upon the degree to which the particular iso-tope is absorbed by the body. Before proceeding several terms will be defined.

SPECIFIC ACTIVITY is the ratio of the amount of the radio-isotope present to the total amount of the element present.

CARRIER is a stable element, naturally occuring in seawater, which is chemically and biochemically similar to the radioisotope in question.

CONCENTRATION FACTOR is the concentration of the radioisotope in the edible portions of seafood divided by the concentration of the radioisotope in the seawater.

A. Specific Activity Method

For those radioisotopes that are absorbed by the body and for which the critical organ is listed by ICRP Publication 2[15] as other than the gastrointestinal tract, the specific activity method has

been used. This method is based upon the following assumptions:

    1. The radioisotope is introduced into the sea in a form such that it acts the same as the stable element or carrier.

    2. The body (both human and marine) is not an isotope separator, that is, uptake, distribution, and biological elimination is the same for the radioisotope as it is for the stable form of the same element.

    3. The chemical makeup of a person who exists on a diet consisting substantially of seafood is no different from that of a person on a normal diet.

    The MPCC may then be defined as the concentration of the radioisotope in seawater such that the specific activity of that radioisotope in the ocean is equal to the allowable specific activity of that radioisotope in the critical organ.

    The allowable specific activity in the critical organ is equal to the maximum permissible burden, q, divided by the amount of stable element or carrier in the organ, I_{nb}. The allowable specific activity in the seawater is equal to the MPCC divided by the concentration of the naturally occuring element or carrier in seawater, I_{nw}.

$$MPCC = \frac{S \; q \; I_{nw}}{I_{nb}} \quad \frac{\lambda + B}{B} \qquad (3.1)$$

where S = factor to relate the civilian population to the industrial
        workers = 0.1

    λ = physical decay constant of the radioisotope

    B = biological decay constant of the carrier

Equation (3.1) includes a decay factor which takes into account the biological half life of the isotope in man. Because of the uncertainties involved in a decay factor for marine species in the food chain, such factors were conservatively disregarded. Derivation of Equation (3.1) and a more complete discussion will be found in NRC Publication 985[14] and Arcuni's "Survey of Underwater Power Reactor Applications."[16] Results of the calculations of MPCC's by the specific activity method are given in Table C-1 of Appendix C.

B. Concentration Factor Method

This method is used for determining the MPCC for all isotopes for which intake is limited by irradiation of the gastrointestinal tract. It is based upon the following assumptions:

1. An individual derives his entire protein diet from marine products. This implies that an individual would eat about 1.5 kilograms of seafood per week.

2. The species of seafood consumed is that species having the highest concentration factor for a specific radioisotope.

3. An individual consumes 15 liters of water per week.

4. The species of seafood remain in an area of contamination a sufficient amount of time to come into biological equilibrium with its surroundings.

5. Radioactive decay of the isotope from the time that the seafood is caught to the time of consumption is ignored.

The gastrointestinal tract as the critical organ means that the intake is limited by the rate at which radioactive material is consumed. The permissible weekly intake is equal to the MPC for

water times the amount of water consumed in one week. The maximum

permissible concentration in seafood is then taken to be this amount

divided by 1.5 kilograms. The MPCC will be the maximum permissible

concentration in seafood divided by the concentration factor, f, or

$$MPCC = \frac{S \times MPC(water) \times 15 \text{ liters}}{1.5 \text{ liters} \times f}$$

$$MPCC = \frac{S \ (MPC) \ (10)}{f} \tag{3.2}$$

where S is equal to the population factor, taken as 1/10 and one

kilogram of seafood has been assumed equal to one liter of seafood.

Results of calculations for radioisotopes in which the uptake

is limited by irradiation of the gastrointestinal tract are given

in Table C-2 of Appendix C.

In both methods, it has been assumed that the only source of

radioactive intake is through marine food products. Any additional

sources would have to be considered by making appropriate allowances

for partial permissible concentrations.

Since, in reality, only a very small segment of the population

will exist solely on a protein source of seafood, a population factor

of 1/10 was selected. This is in keeping with the recommendations of

NBS Handbook 69[4]. If it were felt that a larger portion of the

general population could be affected, a factor of 1/100 might be used.

CHAPTER 4

DETERMINATION OF THE FISSION PRODUCT RELEASE INVENTORY

A maximum hypothetical reactor accident (MHA) is postulated by
TID 14844 and this accident would be equally applicable to undersea
locations with only minor - but significant - modifications. Briefly,
the MHA described in TID 14844 involves   ". . . the complete loss
of coolant upon complete rupture of a major pipe, with consequent
expansion of the coolant as flashing steam, meltdown of the fuel
and partial release of the fission product inventory to the atmos-
phere of the building."[2]

A fixed reactor system located on or slightly above the ocean
floor on a supporting structure could be designed as either a
contained or an uncontained system. For a contained system, the
envelope surrounding the reactor compartment is designed so as to
maintain its integrity in the event of a MHA. The envelope of an
uncontained system is not so designed.

For an uncontained system, it is assumed that occurrence of
a MHA results in the inundation of the system by sea water with a
consequent direct release of fission products to the ocean environ-
ment. The immersion of the reactor components in seawater is
important as certain fission products are soluble in or react with
water. Thus, these soluble fission products are introduced into
the ocean environment. No reduction in the release inventory is
assumed to take place due to plating out of fission products on
reactor component surfaces. Rather, it is assumed that moving masses
of seawater sweep over the reactor system carrying away the entire

fission product release inventory in a single instantaneous "burst" type release. These are regarded as conservative model postulates.

For the contained system, it is assumed that the hydrostatic pressure is greater than the containment pressure. During normal operation, this means a certain amount of leakage of sea water into the reactor structure - a perfectly normal situation which would be routinely handled by pumps. After the MHA, even though the containment vessel remained intact, it is assumed that power to these pumps is interrupted and eventual flooding of the containment structure results. The reactor components are therefore immersed in seawater and the soluble fission products are released to the flooded containment structure. Because the containment structure cannot be absolutely leaktight, it is assumed that the fission products released to the containment leak out to the environment at a constant rate of 0.1 percent per day. Barring a major collapse of the containment structure, this figure would be extremely conservative.

The fundamental assumptions which form the basis for determining the fission product release inventory are given below.

CASE I. UNCONTAINED SYSTEM

1. It is assumed that complete inundation of the reactor system by seawater occurs at the time of the MHA.

2. As a result of this inundation, 100% of the soluble fission products and one percent of the insoluble fission products are released to the ocean environment.

3. No plating out or adhesion to the reactor component surfaces by the soluble fission products occurs.

4. Because of their high solubility in cold water, all
fission product gases are included in the release inventory
and it is assumed that none escape to the ocean surface.

5. The fission product release inventory mixture is assumed to
decay at the same rate as the gross fission product inventory
(see Appendix B, Part 5).

CASE II.   CONTAINED SYSTEM

The assumptions of Case I apply with the addition of the two
assumptions given below.

6. The leakage from the containment structure occurs at the
constant rate of 0.1% per day.

7. Physical integrity of the containment structure is main-
tained throughout the time of interest. The time of interest
extends from the time of the MHA until such time as the
radioactive decay has reduced the fission product release
inventory to negligible levels of activity.

The differences in resultant fission product release inventories
for land based and undersea reactors are highlighted by Table 3. The
assumption that 100% of the solubles are released to the environment
is extremely conservative and accounts for the significant increase
in the undersea reactor release inventory. However, this conservative
assumption is felt to be the only valid approach until future work in
this area provides a sound basis for modification.

The assumption that 100% of the gases are dissolved in the
seawater is conservative in so far as the effects on a person immersed

in the water is concerned. This assumption is not conservative if the
investigation is directed to the effects of airborne radioactivity on
a person on or above the surface of the ocean. Airborne radioactivity
may result from a gaseous fission product bubble rising to the surface.
This is more of a possibility in shallow ocean areas and under in-
stantaneous release conditions. A detailed analysis of the bubble
effect or rising plume effect was not performed.

Table 3. Comparison of Fission Product Release Inventories
for Contained Reactor Systems[a]

	% of Total Inven- tory	PERCENT RELEASED TO CONTAINMENT		PERCENT RELEASED TO ENVIRONMENT	
		TID 14844	UNDERSEA	TID 14844	UNDERSEA
Noble Gases	7.6	100	100	100	100
Halogens	9.5	50	100	25	100
Other Soluble Solids[b]	49.0	1	100	1	100
Insoluble Solids	33.9	1	1	1	1
Gross Fission Product Inventory	100.0	13	66	11	66

a   Percent figures based on total curies (beta and gamma emitters
     included) (see Appendix D).

b   If the elemental state is soluble in or decomposes in water, then
     the total activity due to that fission product is included in
     the category of soluble.

CHAPTER 5

TRANSPORT AND DISPERSION OF FISSION PRODUCTS
IN AN OCEAN ENVIRONMENT

A. Physical Processes of Transport and Dispersion

After the fission product release inventory has been intro-
duced into the ocean environment, it will be subject to several
physical processes. These are (1) molecular diffusion; (2) turbulent
diffusion; (3) physical displacement by large scale currents; (4)
shear effect; (5) depletion through precipitation, adhesion to the
ocean bottom, or uptake by the ecology, and (6) radiological decay.

Molecular Diffusion. Molecular diffusion is due to the random
motion of the molecules of liquid and dissolved substances. It is a
function of the temperature, pressure, and concentration gradients.
However, in comparison with the effects of the turbulent diffusion,
molecular diffusion appears negligible. Although it is generally
neglected in all but extraordinarily calm conditions[17], Okubo[18]
points out that the interaction between molecular and turbulent
diffusion may be important even in large scale phenomenon.

Turbulent Diffusion. Turbulent diffusion arises from the
large and small scale eddies which may be considered as randomly
distributed in both time and space. The eddies span many scales
in size and their effect is perhaps best described by Neumann. "For
a given volume filled with material to be diffused, certain scales of
motion serve only to transport the whole volume, others move the
material around within the volume without spreading it further, and

only a certain intermediate range is effective in spreading the elements of the volume further apart."[7]

One of the complicating factors when considering turbulent diffusion in an ocean environment arises from the fact that the horizontal coefficient of eddy diffusion is proportional to the scale of the disturbance. Weigel illustrates this by pointing out that the rate at which two particles tend to separate increases with increasing distance. At close distances, these particles are moved apart by small scale turbulence only, whereas at greater distances their separation is effected by the larger eddies.[9]

For continuous release of fission products from a point source, the distribution at any particular instant could be represented by a thin ribbon of concentrated fission products meandering through a segment of a circle as shown in Figure 8. At a point downstream from the point of release, the average concentration measured over a period of time would be lower than the concentration in the ribbon because of this meandering. This meandering occurs on all scales of oceanic eddies, and it is important to remember that it is the average distribution rather than the instantaneous conditions which should be observed when concerned with the total radiation dose received. The gradual widening of the narrow ribbons is due to the smaller isotropic eddies, whereas the meandering of the ribbon is due to the intermediate range eddies. The general orientation of the ribbon is, of course, due to the large eddies (mean current).

Physical Transport. Eddies of a scale considerably larger than the area of interest may be considered as anisotropic entities and treated individually. These large scale eddies which are found in
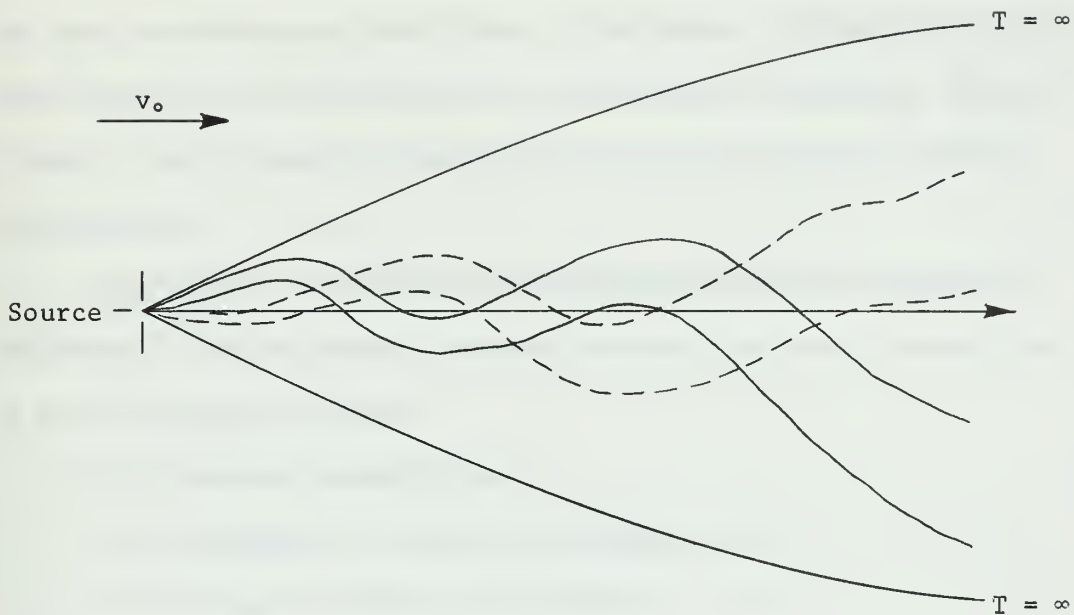
Figure 8. Schematic Plan View of a Diffusing Plume
of Dye from a Continuous Source. (Okubo[18])

the region of interest will tend to move the escaping fission products

in accordance with their mean velocity components. The ocean zones

established in Chapter 2 allow quantitative treatment of these

characteristic currents.

Shear Effect. Because the large scale eddies are anisotropic,

that is, the characteristic length scale is longer in the direction of

mean flow, a nonuniform velocity profile may appear. This velocity

gradient combined with vertical diffusion leads to an effective

horizontal dispersion known as shear effect.[19,20] This, in turn,

leads to elongation of the diffusing cloud of fission products along

the axis parallel to the direction of mean transport.

One of the results of Bowden's[19] investigation of shear effect was that the effective coefficient of horizontal diffusion is inversely proportional to the coefficient of vertical eddy diffusion. That is to say, a stable density gradient increases the horizontal mixing considerably.

Depletion. In addition to radiological decay, reduction of the overall fission product release inventory may occur through any of the following processes:

1. chemical precipitation,

2. absorption to the bottom sediments, and

3. biological uptake by the biota.

Chemical precipitation may occur as a result of the inter-action of certain fission products with the naturally occuring substances in seawater. The resultant insoluble may then settle to the ocean floor. The process of co-precipitation, whereby similar elements are simultaneously removed from solution, may also occur. For instance, strontium is usually co-precipitated and carried along with calcium carbonate.[21]

An even greater portion of the release inventory may be removed from the release cloud through sorptive processes by the bottom sediments. Finely divided organic and inorganic solids may be held in suspension in a layer a few centimeters thick at the ocean floor. These solids have a very definite tendency to absorb (remove from solution) and to hold substances dissolved in seawater.[22]

Uptake of fission products by the biota may take place through adsorption to the surface areas, engulfment, or through metabolic processes.[21] The ability of certain marine organisms to concentrate

radionuclides was discussed in Chapter 3. Subsequent movements by the biota can also contribute to horizontal and vertical dispersion of the inventory. This is particularly true in the case of the extreme vertical migrations of zooplankton which occurs daily.

Radiological Decay. Radiological decay is the only process for which a quantitative estimate of the depletion of the release inventory may be made with any degree of reliability.

B. Fundamental Assumptions

The fundamental assumptions which form the basis for determining the extent of the transportation and diffusion of the fission product release inventory are as follows:

Diffusion Model. Diffusion of the fission product release inventory is assumed to occur in accordance with the three dimensional diffusion model developed by Carter and Okubo.[23] Recommended by Arcuni[16], this model includes shear effect and most accurately predicts the diffusion process over the entire time scale. This model includes the effect of turbulent diffusion due to the large scale eddies in both the horizontal and vertical planes. For completeness, the assumptions used to develop this model include the following:

    a. The horizontal and vertical shear is assumed constant.

    b. The eddy diffusion coefficients in the x-, y-, and z- directions are assumed constant.

    c. The initial concentration is assumed to be a point source.

The first two assumptions do not describe the actual conditions in a turbulent ocean. The actual velocity profile is not linear as

would be required for constant shear terms. Likewise, in turbulent transport, the unsteady motions and eddies of varying scale that are doing the transporting are by no means constant. However, at best, only an average diffusion coefficient can logically be used to define this motion. The basic concept of a diffusion model incorporates average parameters to describe the results of random, turbulent movement.

The assumption of a point source does not accurately describe conditions of leakage from a containment structure. However, this shortcoming may be corrected by using a virtual distance concept. This has been done and results are given in Appendix B, Part 10.

The model, given by Equation (B1.3) of Appendix B, represents the contours of concentration as a set of elongated ellipsoids with common principle axes. The major axis is aligned in the direction of the mean flow. The lengths of these axes vary with time. The degree of elongation depends, apart from time, on the shears, Ω_y and Ω_z, and the eddy diffusivities, A_x, A_y and A_z. The combined effect of the shear and diffusion accelerates the rate of disperson of dye around the center of mass, i.e., the peak concentration in the model.[23]

Current Variance. It is assumed that the velocity and direction of the mean current does not shift during the time of interest. If such shifts occured, a reduction in the concentration could be expected.

Vertical Velocity Component. The mean velocity component in the vertical direction is assumed to be zero. Vertical mixing by the biota and vertical mixing due to thermal effects is neglected. It is assumed that stable stratification exists and vertical mixing is due

to the processes of diffusion only. Any vertical mixing that did occur would reduce the concentration.

Inventory Depletion. Depletion of the fission product release inventory by precipitation, absorption to the bottom, or uptake by the biota is neglected. Any actual depletion that occurs would lead to an overall reduction of the concentration. However, particularly in the shallow depths of Zone I, concentration of fission products on the bottom by these processes could lead to conditions of greater importance. In these ocean floor areas which may be inhabited by commercial marine products, such as oysters, clams, mussels, and other benthic organisms, the equations presented in Section C of this chapter may not be applicable.

Fission Product Decay. A generalized model for the decay of fission products is assumed. In this model, no decay is assumed during the first 1000 seconds after shutdown. After this time, it is assumed that the fission product release inventory decays as $k\, t^{-1.2}$. The assumption of no decay during the first 1000 seconds after shutdown may at first appear too conservative. However, it is in part offset by the fact that fission products with a half life of less than four minutes are not included in the release inventory. The overall effect of these assumptions is conservative in that the decay rate for the higher energies of the gamma ray spectrum fall off faster than do the lower energies with a resultant softening of the spectrum with time.

Reflection from the Ocean Floor. It is assumed that the reflective effect from the ocean floor can be treated by adding the image with respect to the ocean floor. This is conservative in that

adhesion by the bottom sediments would result in considerably less than 100% reflection.

Boundary Effects. The boundary effect of the sea surface and the thermocline is neglected. For Ocean Zones II, III, and IV, such an assumption is reasonable due to the extremely limited vertical diffusion. However, for Zone I, this assumption is not conservative. Rather the reflection at the thermocline or the sea surface would lead to higher concentrations.

Steady State Conditions. In the continuous release case, it is assumed that steady state conditions are established instantaneously. This is extremely conservative in the investigation of locations a great distance from the point of release with slow currents. For points near the release or for high currents, the assumption is reasonable, and it greatly simplifies the mathematics.

Shielding Effect. In determining direct gamma dose, the effect due to the contained fission products is neglected and only the gamma dose due to the cloud passage is considered. Because of the shielding effect of the water, at distances greater than 10 meters from the containment, the contribution of the fission products within the containment towards the total dose received is negligible. Also, because of the shielding effect of the water and the fact that inhalation is not possible, gamma radiation of less than 0.1 Mev energy, all alpha, and all beta radiation is neglected in dose determinations.

C. Mathematical Models

With the assumptions as presented in the preceding section, it

is possible to derive equations which describe the physical transport
and dispersion of the radioisotopes that are assumed to be released
in the event of a MHA at a reactor sited on the ocean floor. This
has been done in Appendix B for both the contained and uncontained
reactor systems.

For the uncontained reactor system, the total (integrated) dose
received as a function of distance from the reactor and mean current
velocity is given by the following equation:

$$I'(x_o, v_o) = \int_0^{10^3 \text{ sec}} D(t,x_o,v_o)dt + \int_{10^3}^{T} k\, t^{-1.2}\, D(t,x_o,v_o)dt \qquad (5.1)$$

where $D(t,x_o,v_o)$ = dose rate due to fission products in the water as
a function of time after release, distance from
the reactor, and mean current velocity.

T = time after release

k = normalization constant for the decay of mixed fission
products

This equation forms the basis for determining the exclusion radius and
the low population radius – the only difference being the selection of
the upper limit, T, as four hours or as infinity. The exclusion radius
or low population radius is the value of x_o such that the dose evalu-
ated by Equation (5.1) is 25 rem. The equation which forms the basis
for determining the safety radius is given by the following
expression:

$$MPCC = \frac{M_i\, \alpha\, e^{-\lambda_i t}}{t^{3/2}\, \sqrt{1 + \beta\, t^2}} \qquad (5.2)$$

where

$$\alpha = \frac{1}{8\pi^{3/2} (A_x A_y A_z)^{1/2}} \tag{5.3}$$

$$\beta = \frac{1}{12} (\Omega_y^2 \frac{A_y}{A_x} + \Omega_z^2 \frac{A_z}{A_x}) \tag{5.4}$$

and M_i = the total activity (curies) of radioisotope i, released to the environment.

λ_i = decay constant for radioisotope i.

Equation (5.2) may be solved for t, the time after release at which the peak concentration of the isotope equals the MPCC. By knowing the mean current velocity, a safety radius may then be established.

For the contained reactor system, the applicable equation for exclusion radius or low population radius calculations is given by Equation (5.5) where T equals 4 hours, or T equals infinity.

$$I'(x_o, v_o) = (10^3 \text{sec}) D'(x_o, v_o) + D'(x_o, v_o) k \int_0^T t^{-1.2} dt \tag{5.5}$$

where $D'(x_o, v_o)$ = instantaneous steady state dose rate as a function of distance from the reactor and mean current velocity.

As in the uncontained case, the exclusion radius or low population radius is the value of x_o such that the dose, when evaluated by Equation (5.5) is equal to 25 rem.

For safety radius determinations, Equation (5.6) applies.

$$MPCC = M_i \ell e^{-\lambda_i t} \int_0^\infty \psi(t, x_o, v_o) dt \tag{5.6}$$

where ℓ =   leak rate

              $\psi(t,x_o,v_o)$ =   function defined by Equation (B6.1) which is the basic mathematical diffusion model as determined by Carter and Okubo (Ref. 27).

Because of the instantaneous, steady state assumption, the highest concentrations (and therefore the limiting concentrations) occur at $t = 0$, or before radioactive decay begins. The safety radius is that value of x_o such that the concentration as evaluated by Equation (5.6) at $t = 0$ is equal to the MPCC.

CHAPTER 6

RESULTS

A computer program, SEADIF, has been written which will
calculate the exclusion radius, low population radius, the direct
gamma dose rate four hours after release, and the time (or in the
contained case the distance) required for the peak concentration of
each fission product radioisotope to fall below MPCC. SEADIF consists
of two separate and complete programs, the use of which is determined
by whether it is a contained or uncontained reactor system.   The
following data must be read in by the computer in proper format:

    a.   Power level of the reactor

    b.   Diffusion and shear coefficients

    c.   Current velocity

    d.   Distance from the containment

    e.   Containment diameter (optional input)

    f.   Isotope information for all fission products of

         consequence, including amount per megawatt, MPCC,

         half life, percent decay by gamma energy group,

         and solubility information

    g.   Containment leakage rate (contained case only).

The computer program and input data format is present in Appendix E.

A.   Uncontained System

    The exclusion radius, by definition, depends upon the total
dose received in the first four hours after initial release. This
total dose will be a function of the distance away and the mean

current velocity. Figure 9 depicts the four hour dose as computed by SEADIF for typical current velocities and diffusion coefficients. There are several interesting features of this set of curves.

First, for high velocities and relatively short distances from the release point, the total dose received is independent of the mean current velocity and inversely proportional to the distance. Although higher velocity conditions will mean that a higher concentration of fission products will be carried a certain distance, this concentration passes over the point of interest in a shorter time with the net result being an identical total dose received.

Velocity dependence enters the picture when the fission product cloud (defined as extending a distance of 3σ) has not completely passed over the point in question within 1000 seconds after release. This is because at t equal to 1000 seconds, it has been assumed that radio-active decay begins. It now depends upon the time at which the cloud passes over as to the total dose received.

A second interesting feature of Figure 9 is the departure from a linear representation on a log-log plot. This occurs when the fission product cloud has not completely passed over the point in question after four hours.

If radiological decay is ignored, the results will be as shown in Figure 10. Comparison of Figures 9 and 10 illustrate the effect of radiological decay. As is to be expected because of the basic decay assumptions, if the entire cloud passes over the point in question within 1000 seconds after release, there is no difference in the dose received. Figures 9 and 10 are based on the same fission product release inventory, that is, fission products with a half life of

Figure 9.   Four Hour Dose as a Function of Distance
             (with decay) for an Uncontained 10 MW(t)
             Reactor with Diffusion Coefficient Data Set 1

Figure 10.   Four Hour Dose as a Function of Distance (with-
out decay) for an Uncontained 10 MW(t) Reactor
with Diffusion Coefficient Data Set 1

less than four minutes are not included in either case.

One of the major considerations with regard to removal of personnel from the area of an undersea reactor will be the dose rate "picture" at four hours, an example of which is shown in Figure 11. For a 10 MW(t) reactor and a mean current velocity of 20 centimeters per second the exclusion radius is 570 meters. From Figure 11 it may be seen, however, that at 570 meters the dose rate at four hours is essentially zero since the entire cloud has passed. Therefore, after four hours no additional dose would be received by personnel within that distance from the reactor.

This points up a very important concept. For an uncontained reactor system the low population distance is, except for extremely small mean current velocities, the same as the exclusion radius. Again, this is due to the fact that once the cloud has passed over the point in question the dose rate in that vicinity is negligible. This concept is different from the concept presented in TID 14844 because of the fact that in an atmospheric environment the dose due to the fission products in the containment building is significant.[2] Because of the shielding effect of the water this is not the case for an undersea location. Figure 12 illustrates the difference between the four hour dose and the infinite dose, these doses forming the basis for the exclusion radius and low population radius respectively. It is seen that differences are apparent only at total doses well below the 25 rem limit.

A great deal of uncertainty lies in the selection of appropriate diffusion and shear coefficients. Two representative diffusion coefficient data sets were chosen based upon parameters presented by
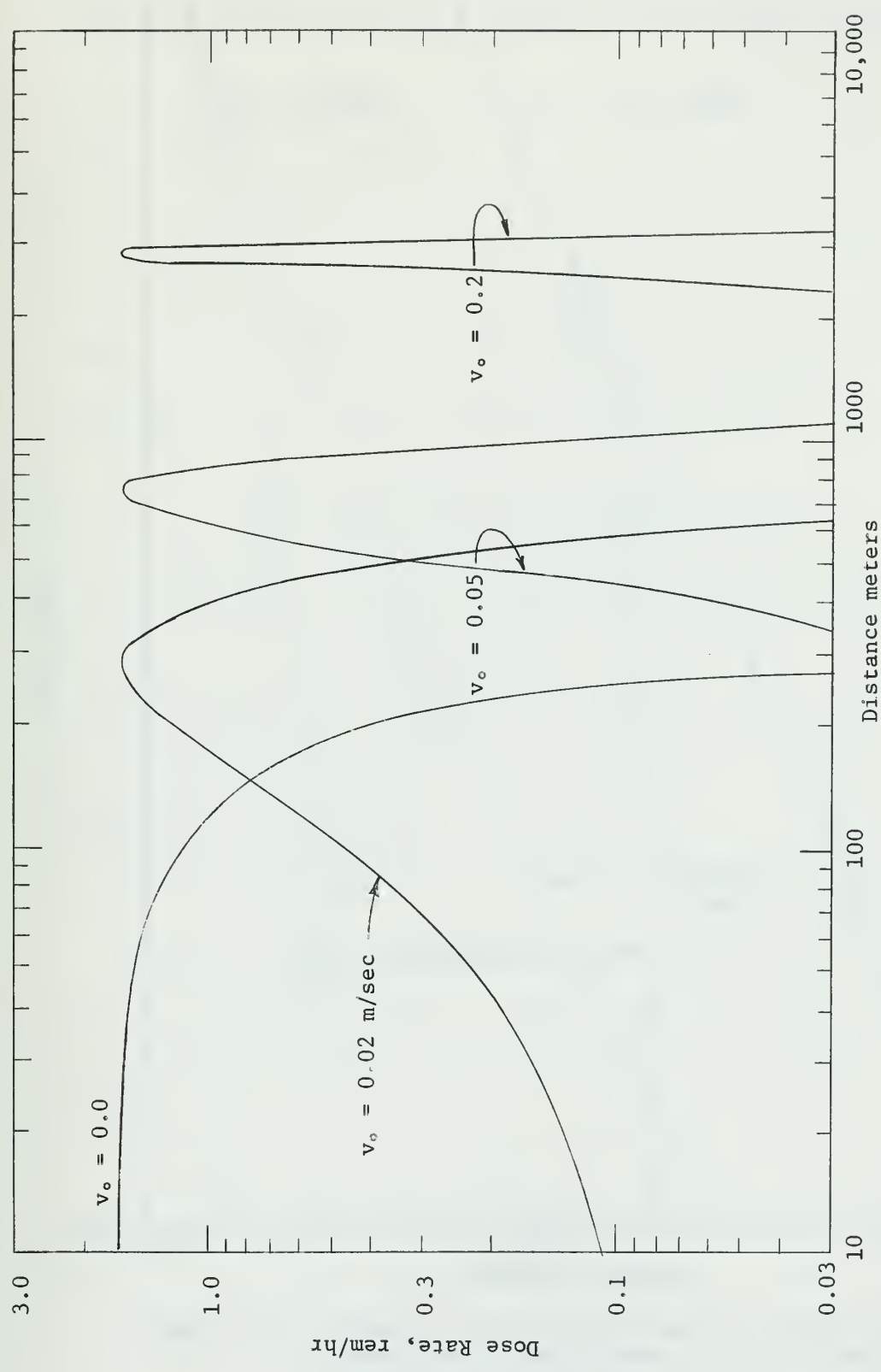
Figure 11. Dose Rate at Four Hours After Instantaneous Release (with decay) for Various Current Velocities for an Uncontained 10 MW(t) Reactor with Diffusion Coefficient Data Set 1
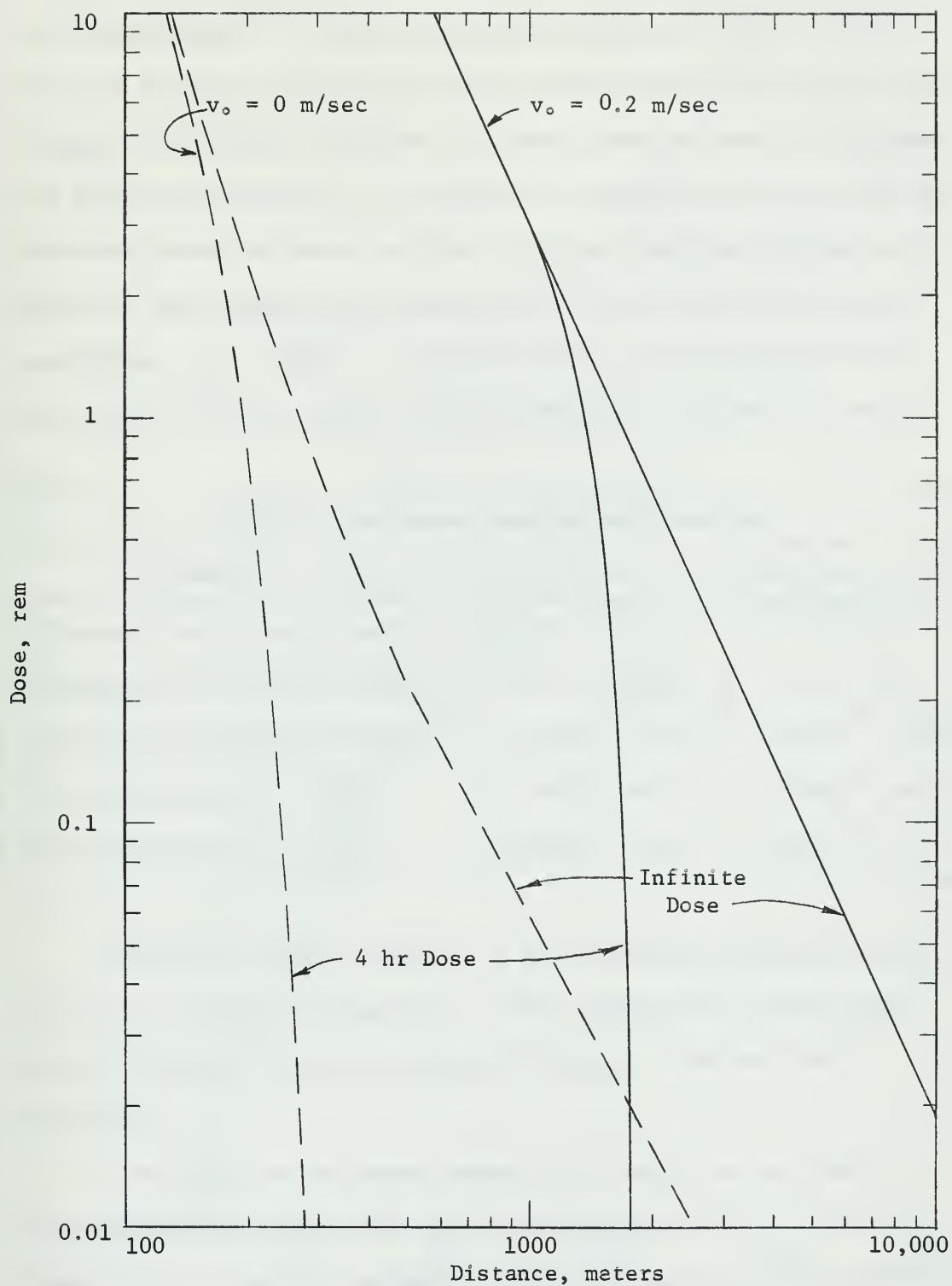
Figure 12.   Infinite and Four Hour Dose (with decay) for an
Uncontained 10 MW(t) Reactor with Diffusion
Coefficient Data Set 1

Carter and Okubo.[23] These two data sets, shown in Table 4, define a
range of realistic diffusion and shear coefficients but should not be
thought of as totally inclusive. Unless otherwise noted, all figures
are based upon data set 1. The effect of changing data sets upon the
exclusion radius is shown in Figure 13. One important difference in
these two data sets is in the selection of the vertical diffusion
coefficient, A_z. Figure 14 shows the effect of varying this coeffi-
cient alone over the range of values presented by Carter and Okubo.

Table 4. Diffusion Coefficient Data Sets		
Parameter	Data Set 1	Data Set 2
Diffusion Coefficient, x-axis, A_x	0.39 m^2/sec	0.39 m^2/sec
Diffusion Coefficient, y-axis, A_y	0.39 m^2/sec	0.39 m^2/sec
Diffusion Coefficient, z-axis, A_z	1.9×10^{-3} m^2/sec	0.9×10^{-4} m^2/sec
Shear Coefficient, $\Omega_y = \dfrac{dv}{dy}$	1.6×10^{-6} sec^{-1}	1.0×10^{-4} sec^{-1}
Shear Coefficient, $\Omega_z = \dfrac{dv}{dz}$	1.8×10^{-3} sec^{-1}	6.6×10^{-3} sec^{-1}

Results are also sensitive to the horizontal diffusion coeffi-
cient, A_x, as shown in Figure 15. This coefficient is much larger
than A_z because of the much greater diffusion in the horizontal
directions.

The effect of the shear terms is not nearly so noticeable.
Shear coefficients enter into the calculations of β only (defined by
Equation (5.4)) and the exclusion radius results are rather insensitive
to this term. However, where these terms do effect results is in the
peak concentration calculations. The larger that Ω_z is, the greater
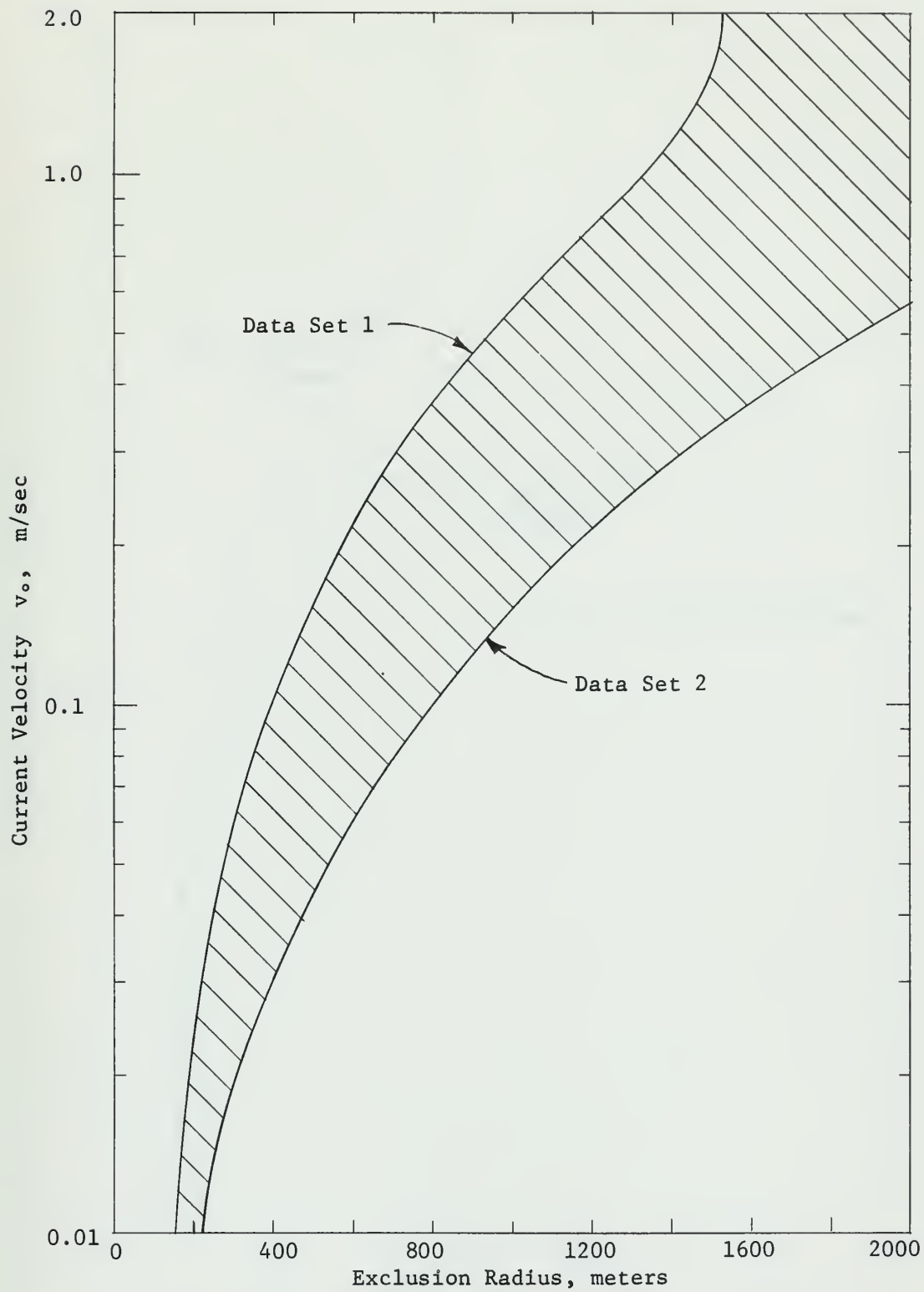
Figure 13.   Exclusion Radius Determination for an
Uncontained, 10 MW(t) Reactor
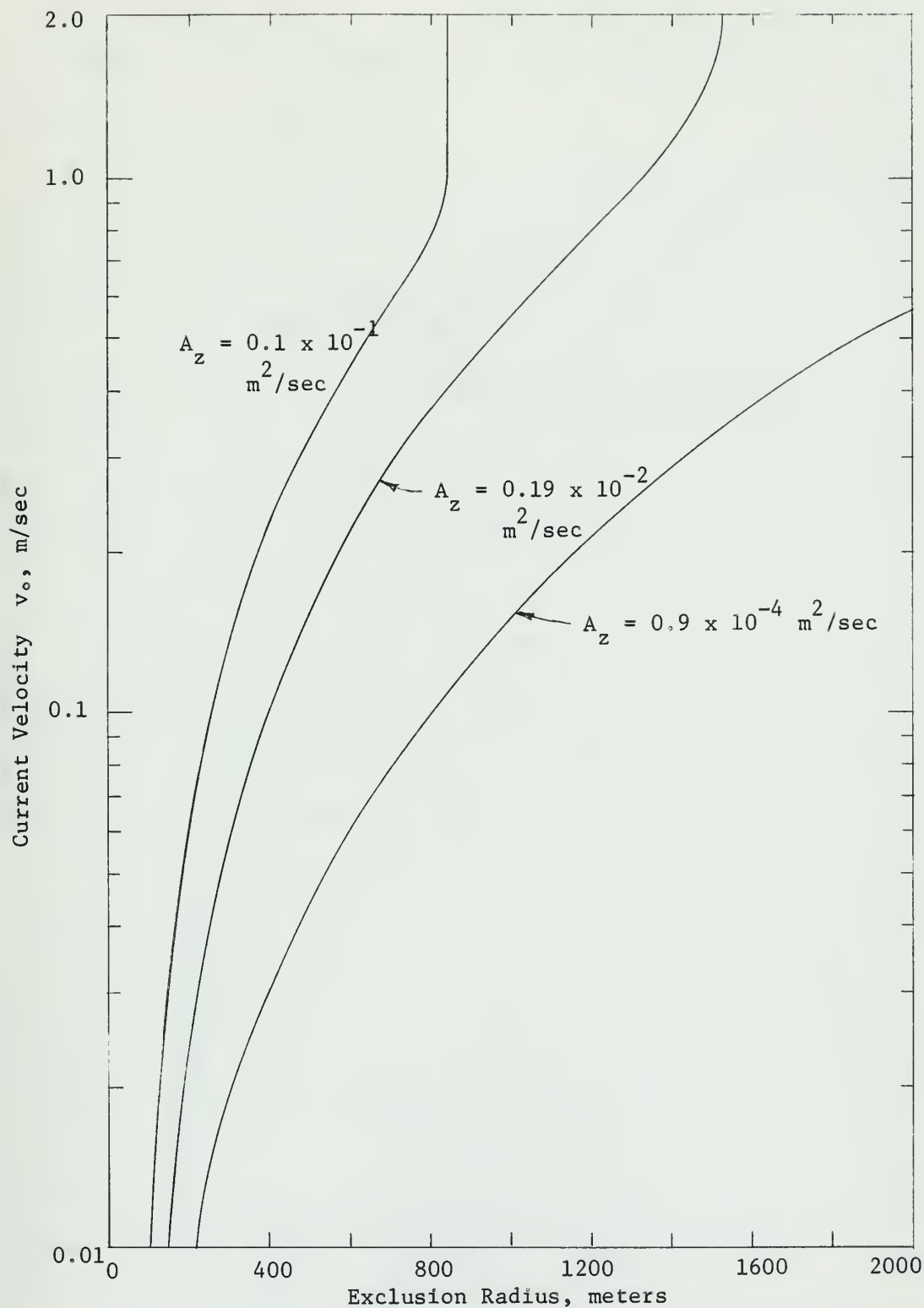
Figure 14. Effect of Variation of Vertical Diffusion
Coefficient, A_z, on Exclusion Radius for
an Uncontained, 10 MW(t) Reactor
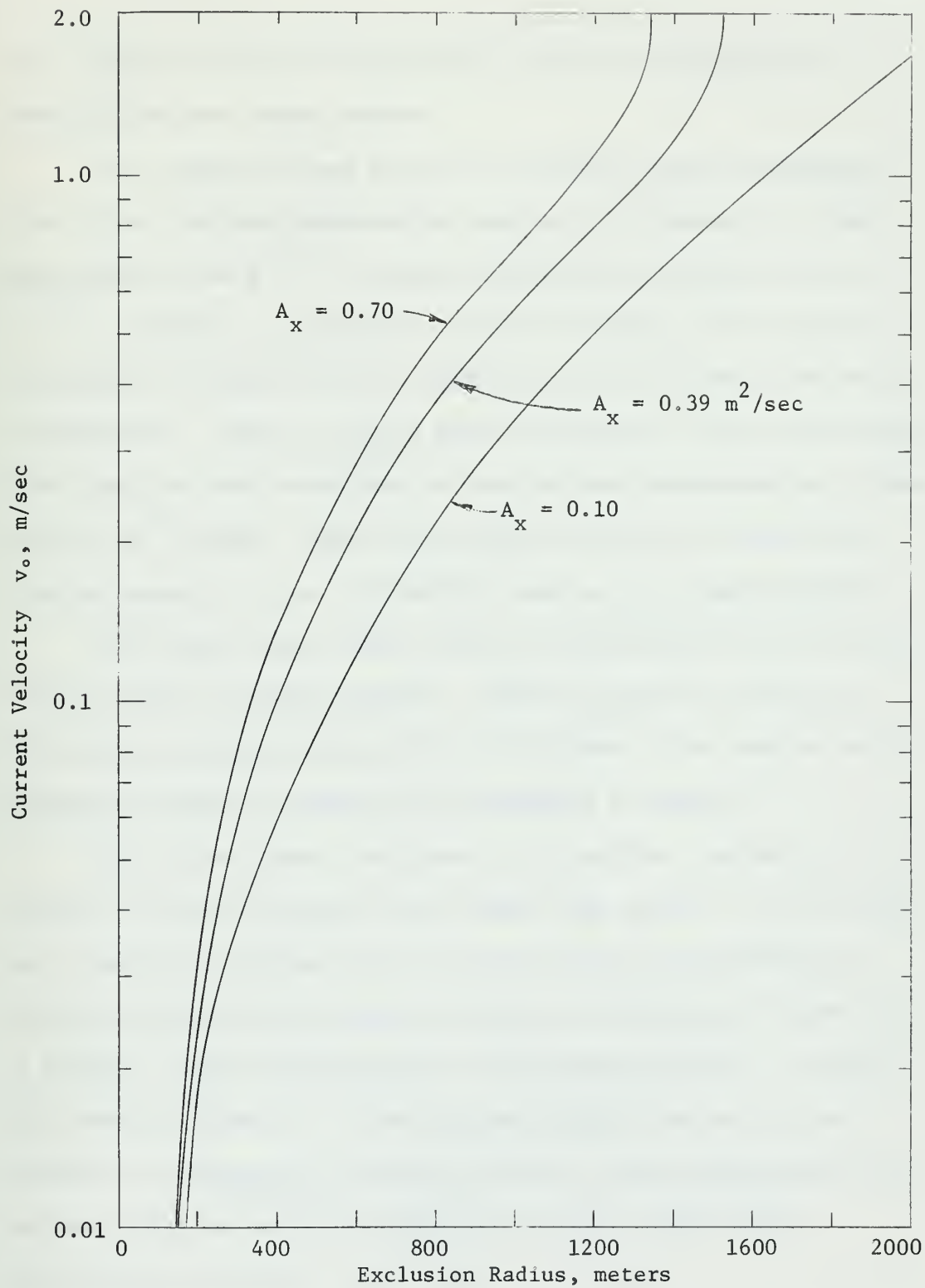
Figure 15. Effect of Variation of Horizontal Diffusion
Coefficient, A_x on Exclusion Radius for an
Uncontained, 10 MW(t) Reactor

the elongation of the diffusing cloud. This has the effect of reducing the peak concentration.

For times much less than $\beta^{-1/2}$ it may be seen from Equation (B6.9) that the peak concentration goes as $t^{-3/2}$ whereas for times much greater than $\beta^{-1/2}$ the peak concentration is proportional to $t^{-5/2}$. Therefore, by varying β the rate of change of the peak concentration can change. Beta is affected by both diffusion and shear coefficients. Figure 16, which shows the change in peak concentration with time, has been normalized so that the peak concentration is equal to 1 at 10^3 seconds. Figure 16 is applicable only to long lived fission products in that radioactive decay has not been included.

The reactor power enters into the calculations by way of the fission product release inventory. The dose rate and total dose received are directly proportional to the power. The results for the exclusion radius are graphically represented in Figure 17.

Up to this point, the effect of the surface boundary and the extent of vertical diffusion has largely been ignored. The dose rate as a function of distance above the ocean floor was determined at times of four hours and eight hours after instantaneous release for a 10 MW(t) reactor using diffusion coefficient data set 1. Results are shown in Figure 18. It may be seen that as long as the sea surface or thermocline is greater than about twenty meters above the release point the assumption that the boundary effect may be neglected is valid for a time frame of a few hours.

More important, as long as the reactor location is not in the vicinity of upwelling or in shallow waters where vertical mixing extends to the bottom, it is not likely that short half life
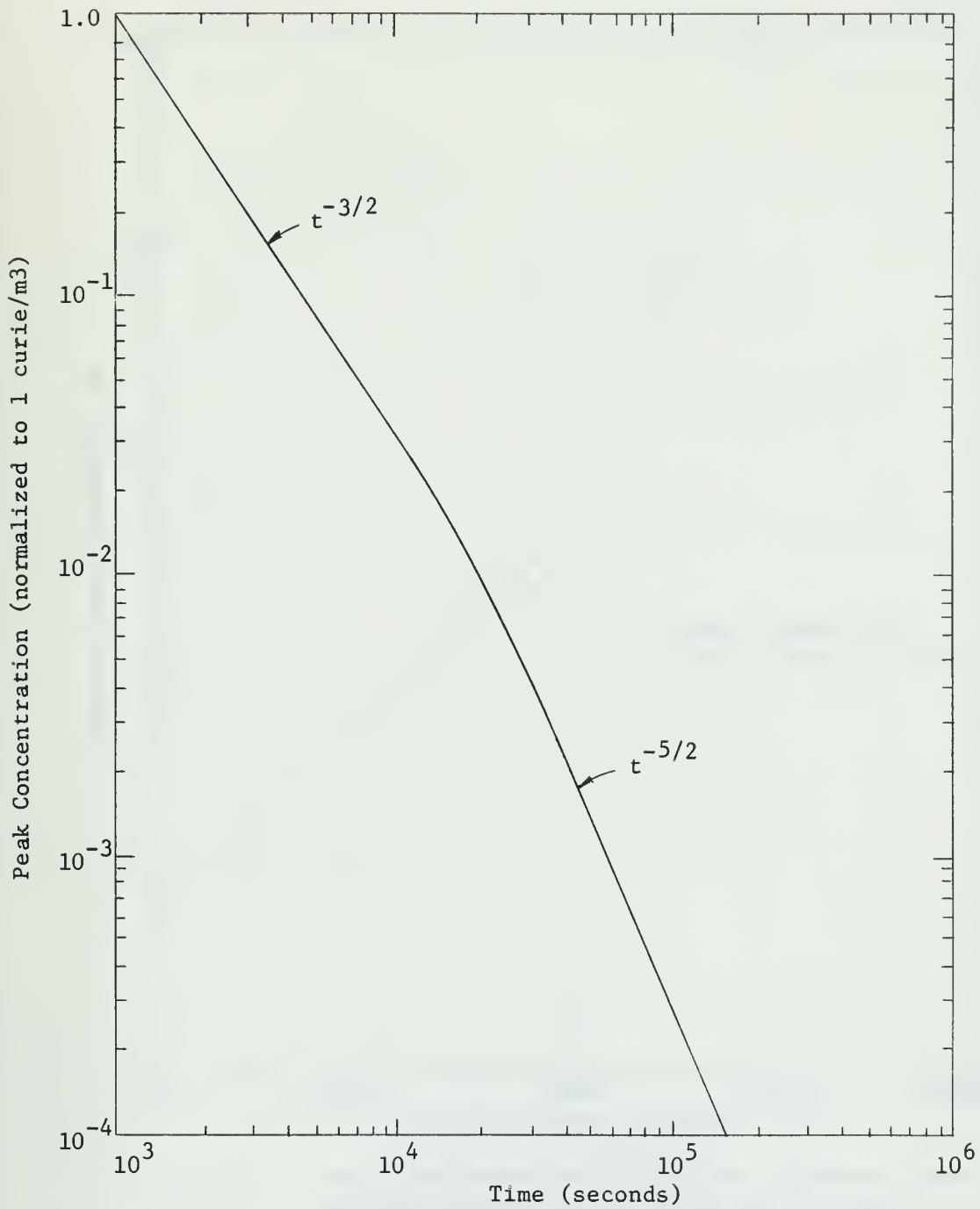
Figure 16.   Variation of Peak Concentration
             with Time for Long Lived Fission
             Products
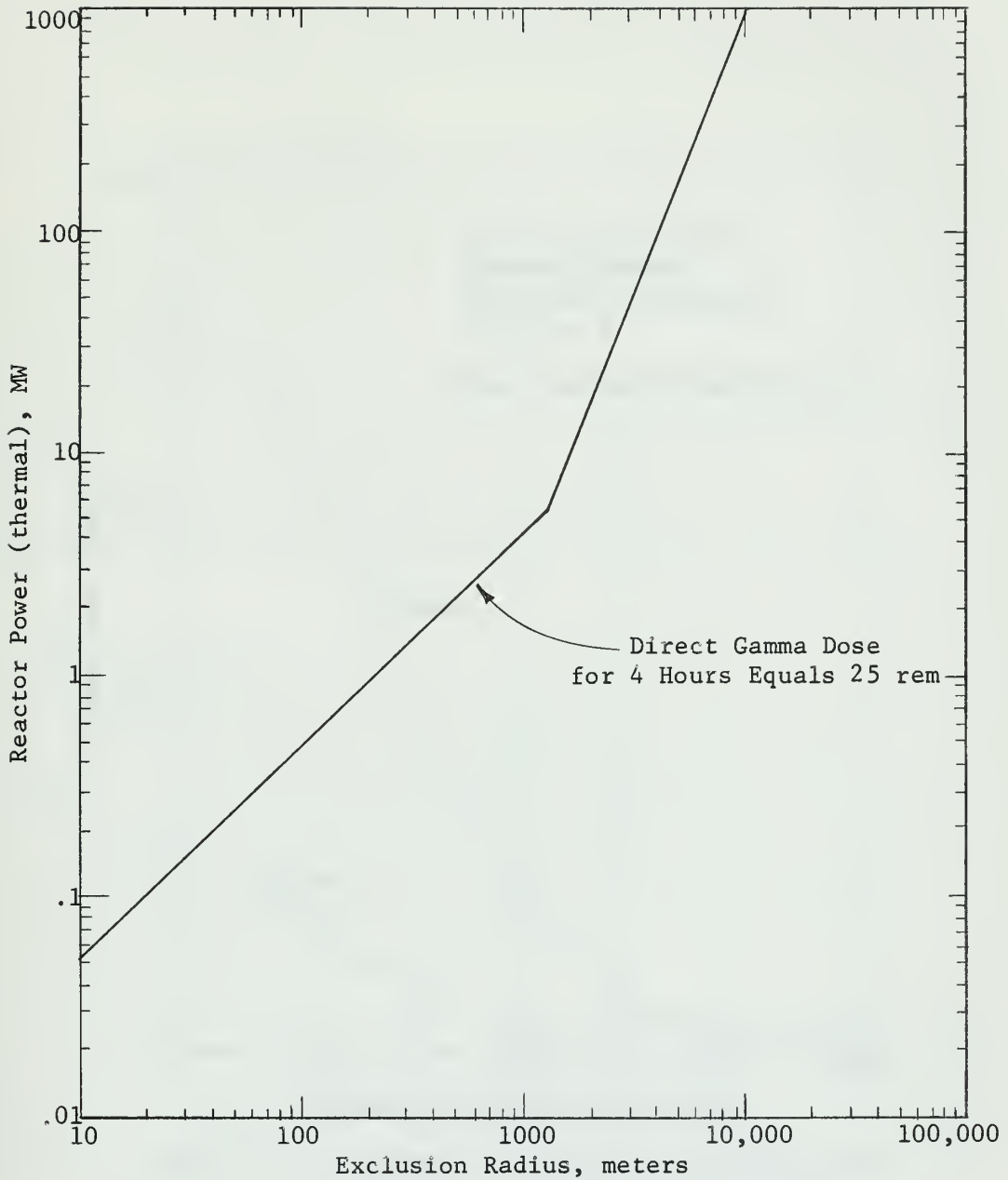
Figure 17.   Exclusion Radius as a Function of Reactor Power
for Uncontained Reactor Systems with a Mean
Current Velocity v_o = 1 m/sec and Diffusion
Coefficient Data Set 1
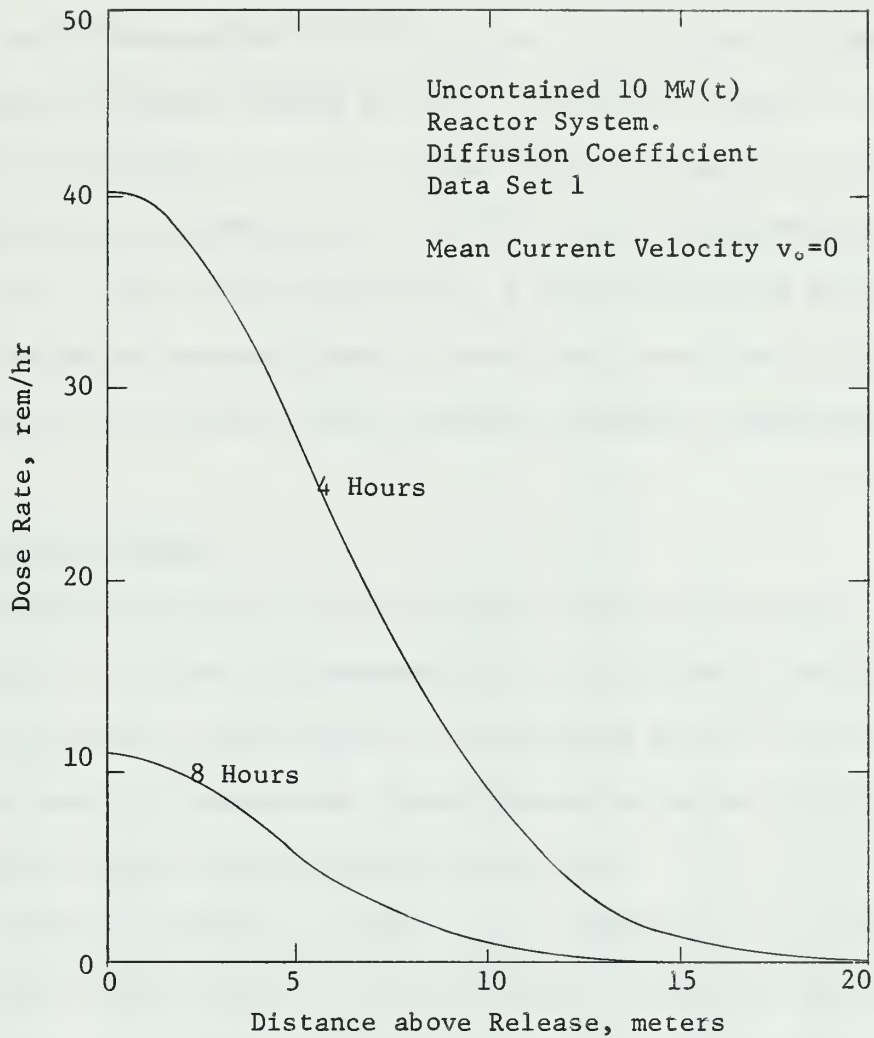
Figure 18. Dose Rate at 4 Hours and 8 Hours after
Release as a Function of Distance,
z above Release Point

radioisotopes, in harmful amounts, will extend to the mixed layer.
Therefore, contamination of surface vessels by radioisotopes with a
short half life is not likely.

For an uncontained 10 MW(t) system, the critical isotope in
determining the safety radius is Te^{129m} as shown in Figure 19. Using
diffusion coefficient data set 1 (shaded bars on Figure 19) the time
required for the concentration of Te^{129m} to fall below MPCC is 2,130
hours. For a mean current velocity of 1 meter per second the potential
safety radius is extremely large. Under these conditions, the
assumption of no current variance becomes extremely conservative.

B. Contained Systems

Despite the conservative assumption that steady state
conditions are achieved instantaneously it may be seen from Figure 20
that the four hour dose figures for a contained 10 MW(t) system are
extremely small. Furthermore, these figures are not as velocity
dependent as in the case of uncontained systems.

Briefly examining the steady state assumption, it is noted that
this is most conservative for extremely small velocities and large
distances. For instance, at 1000 meters and 1 centimeter per second
current velocity conditions, the initial activity released in the
course of a MHA would not begin to arrive until approximately 10^5
seconds after initiation of the MHA. Therefore, the four hour dose
would be zero. However, Figure 20 reflects a four hour dose for
these conditions in excess of 10^{-3} roentgen.

The main point is that before serious consequences due to the
direct gamma dose are experienced, an increase by a factor of 100 to
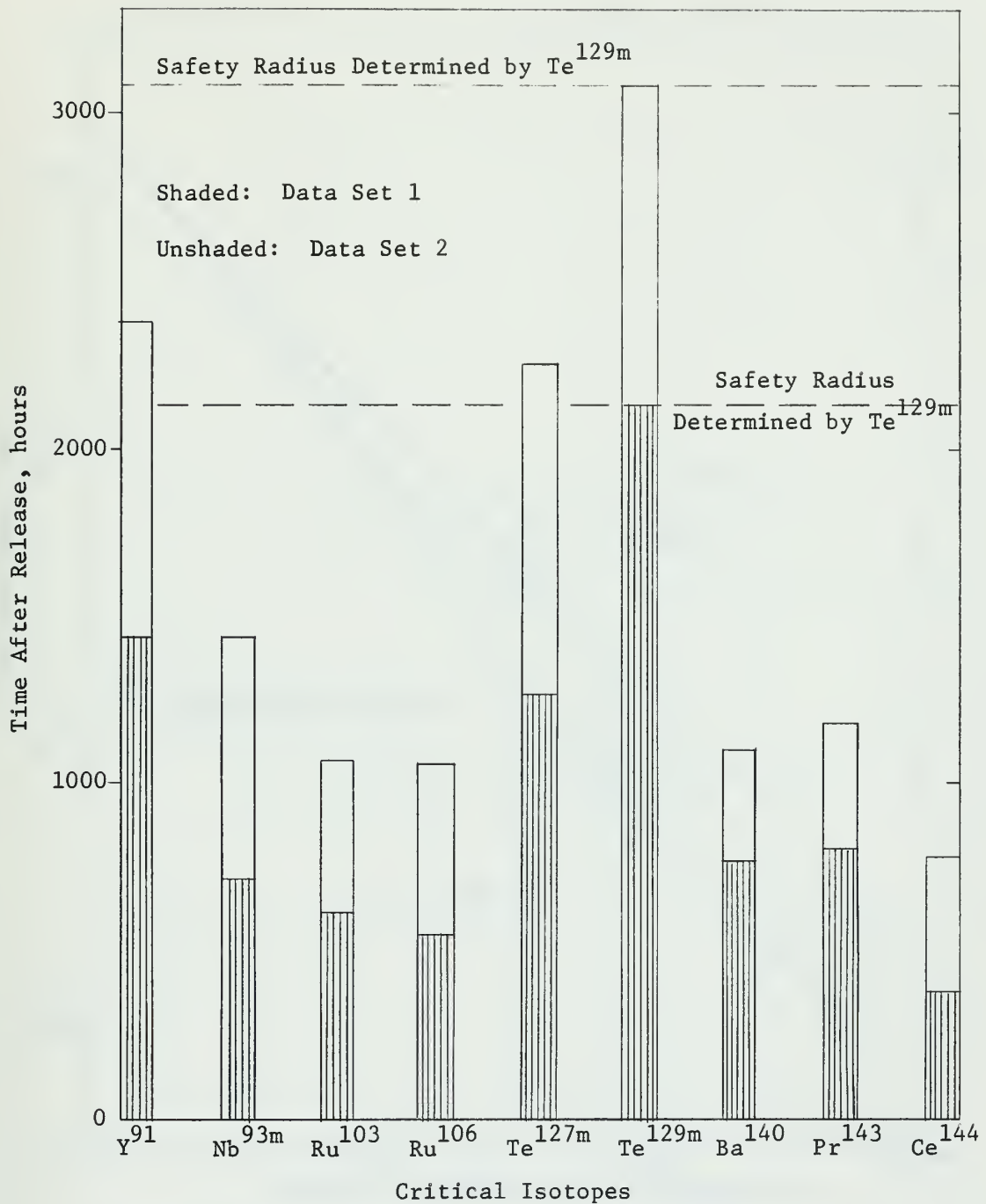
Figure 19. Time Required for Concentration of Critical Isotopes to Fall Below MPCC for an Uncontained 10 MW(t) Reactor
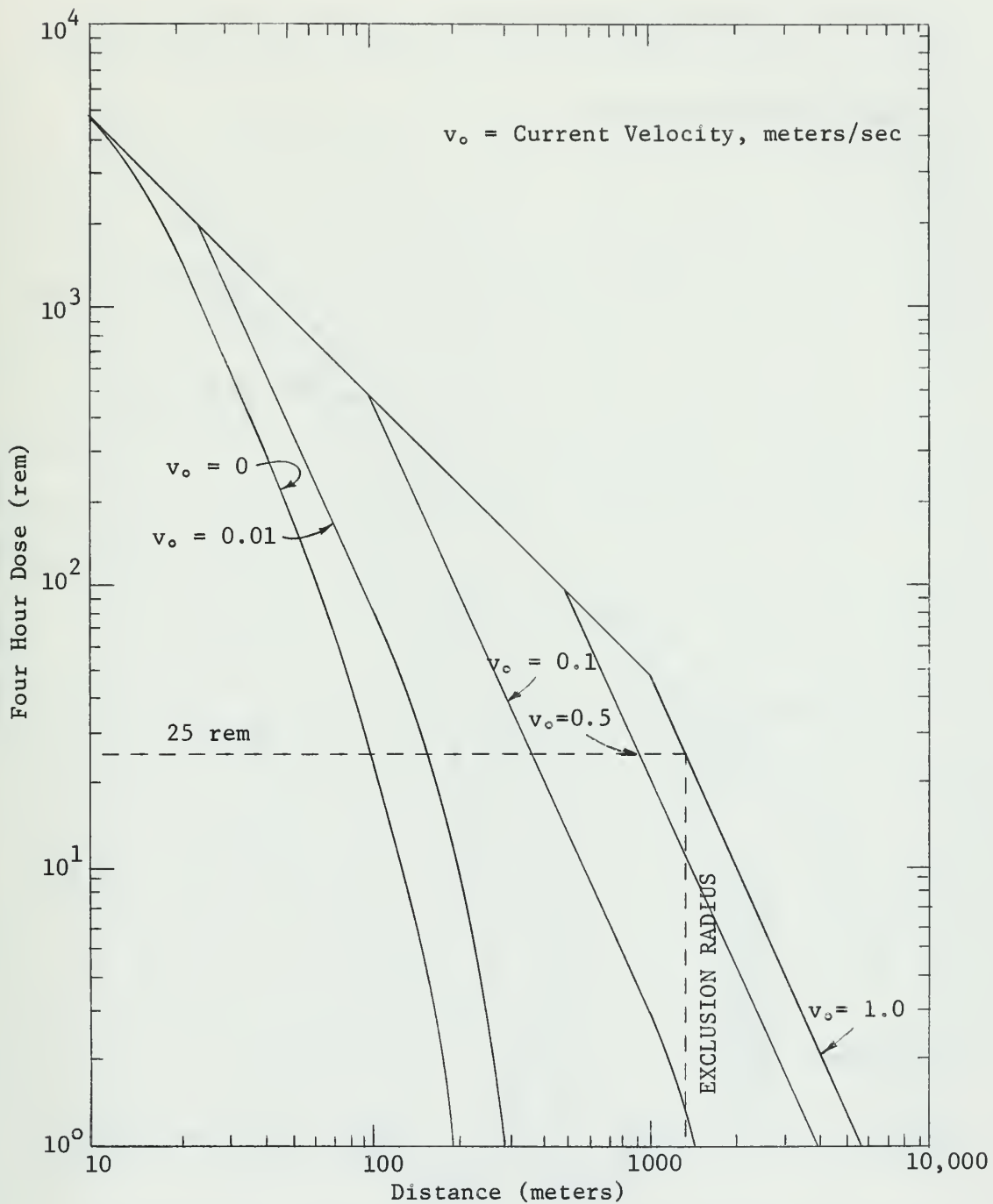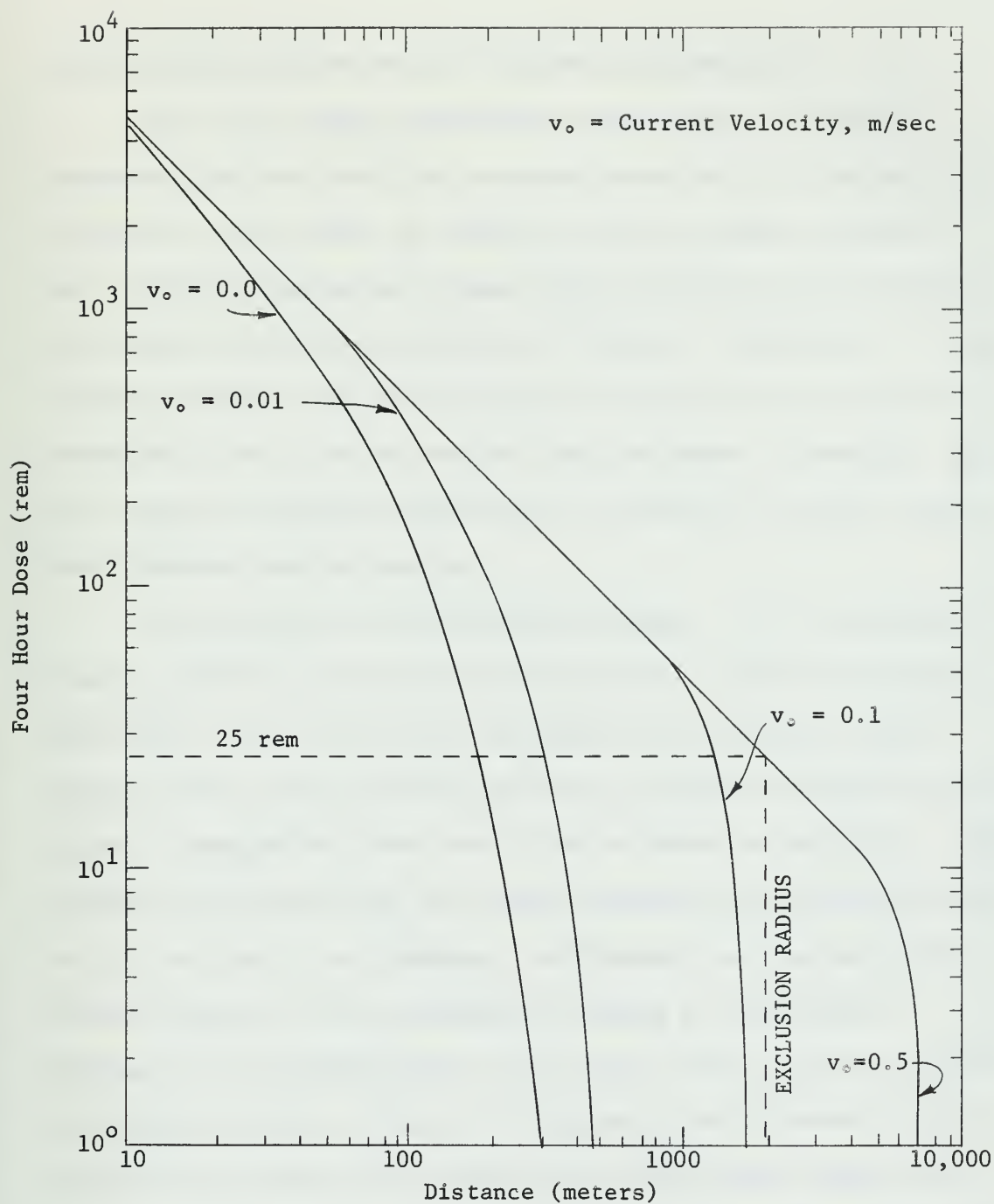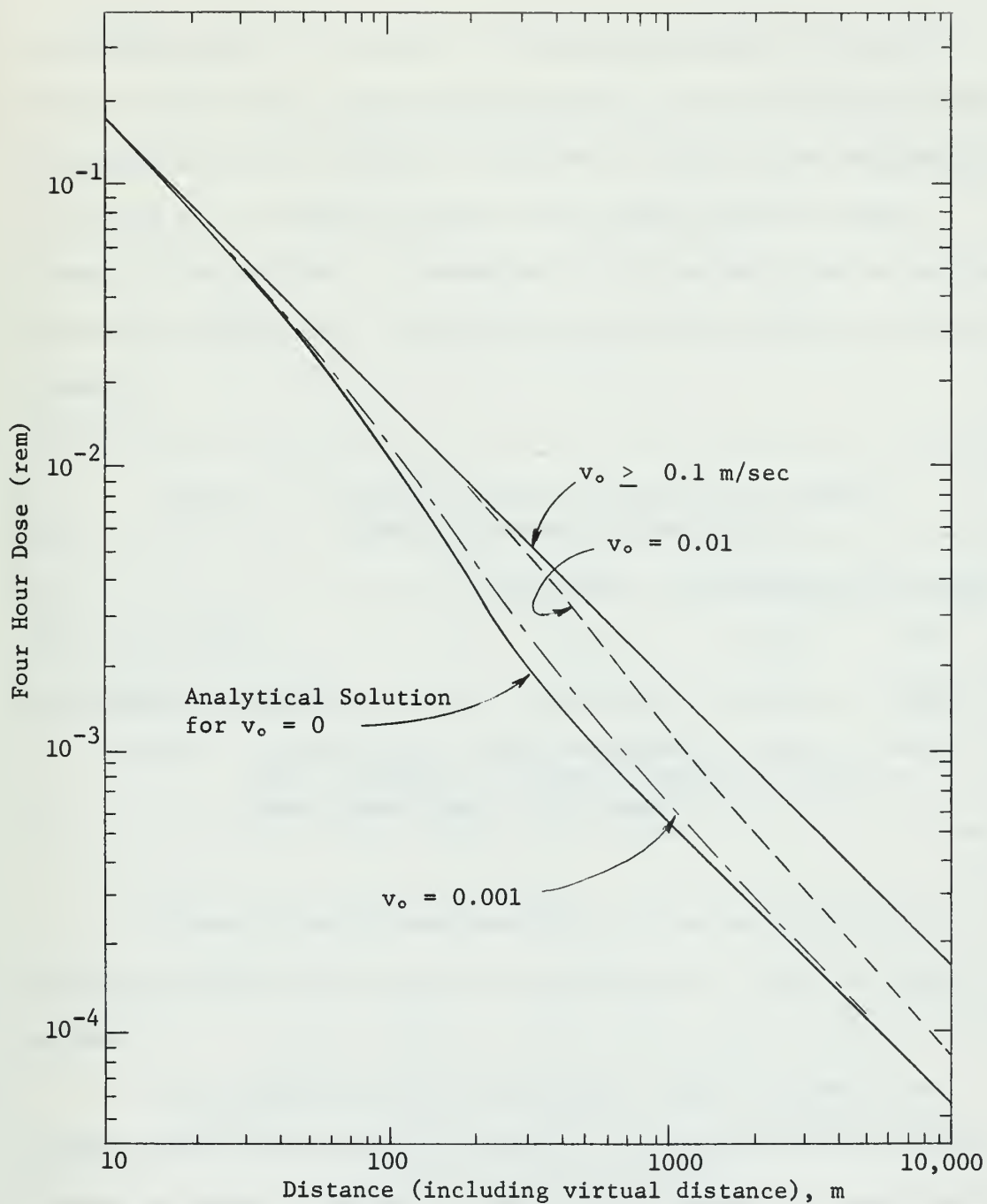
Figure 20.   Four Hour Dose as a Function of Distance
              (with decay) for a Contained 10 MW(t) Reactor
              with Diffusion Coefficient Data Set 1

1000 would have to be incurred. An exclusion radius or low popu-
lation radius has no real significance for a contained reactor system
until power levels in excess of 1000 MW(t) or leak rates considerably
in excess of 0.1 percent per day of the fission product release
inventory are realized. A comparison of the exclusion radius and low
population radius for a contained and uncontained system is shown in
Table 5.

Table 5. Siting Distances (in meters) for 10 MW(t) Reactor Located in Ocean Zone II			
	Contained	Uncontained	TID 14844
Exclusion Radius	< 20	1340	220
Low Population Radius	< 20	1340	800[a]

Note (a): Low population radius determined on basis of iodine
dose to thyroid. Limiting distance on basis of
direct gamma dose is 250 meters.

Figures 21 and 22 show the effect of the variation of the
diffusion coefficients on the four hour dose for a contained reactor
system.

The principal concern in contained reactor systems is the
safety radius determination. Results of calculations for a 10 MW(t)
system are shown in Figure 23. The critical isotope for Ocean Zone II
with a mean current velocity of 1 meter per second is Nb^{93m} with a very
long half life (32,400 hours) and a very low natural abundance of its
carrier, the element Niobium, in seawater (1×10^{-8} grams per kilo-
gram). These two factors outweigh the fact that the fission product
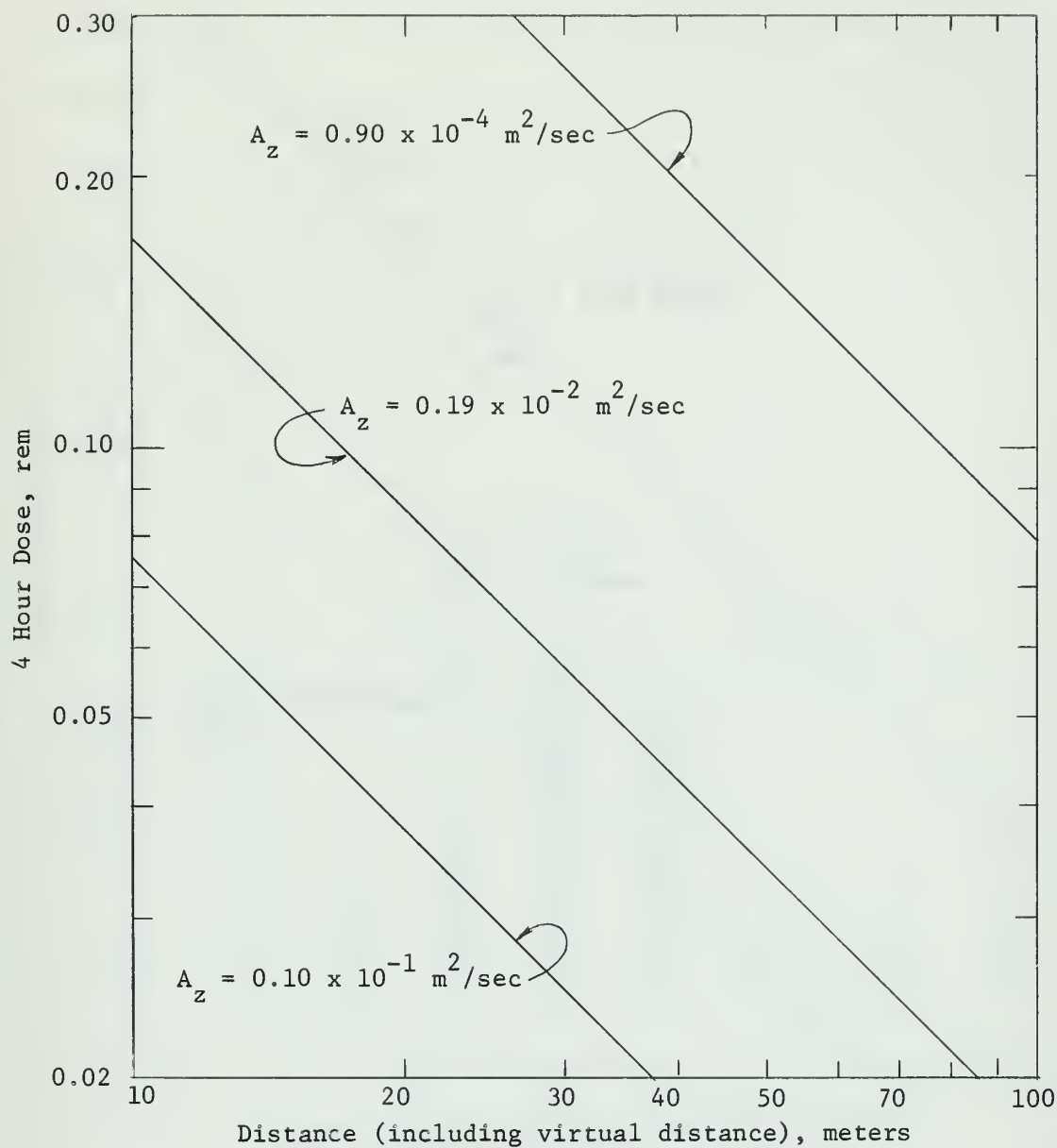
Figure 21. Effect of Variation of Vertical Diffusion Coefficient, A_z, on 4 Hour Dose for a Contained 10 MW(t) Reactor
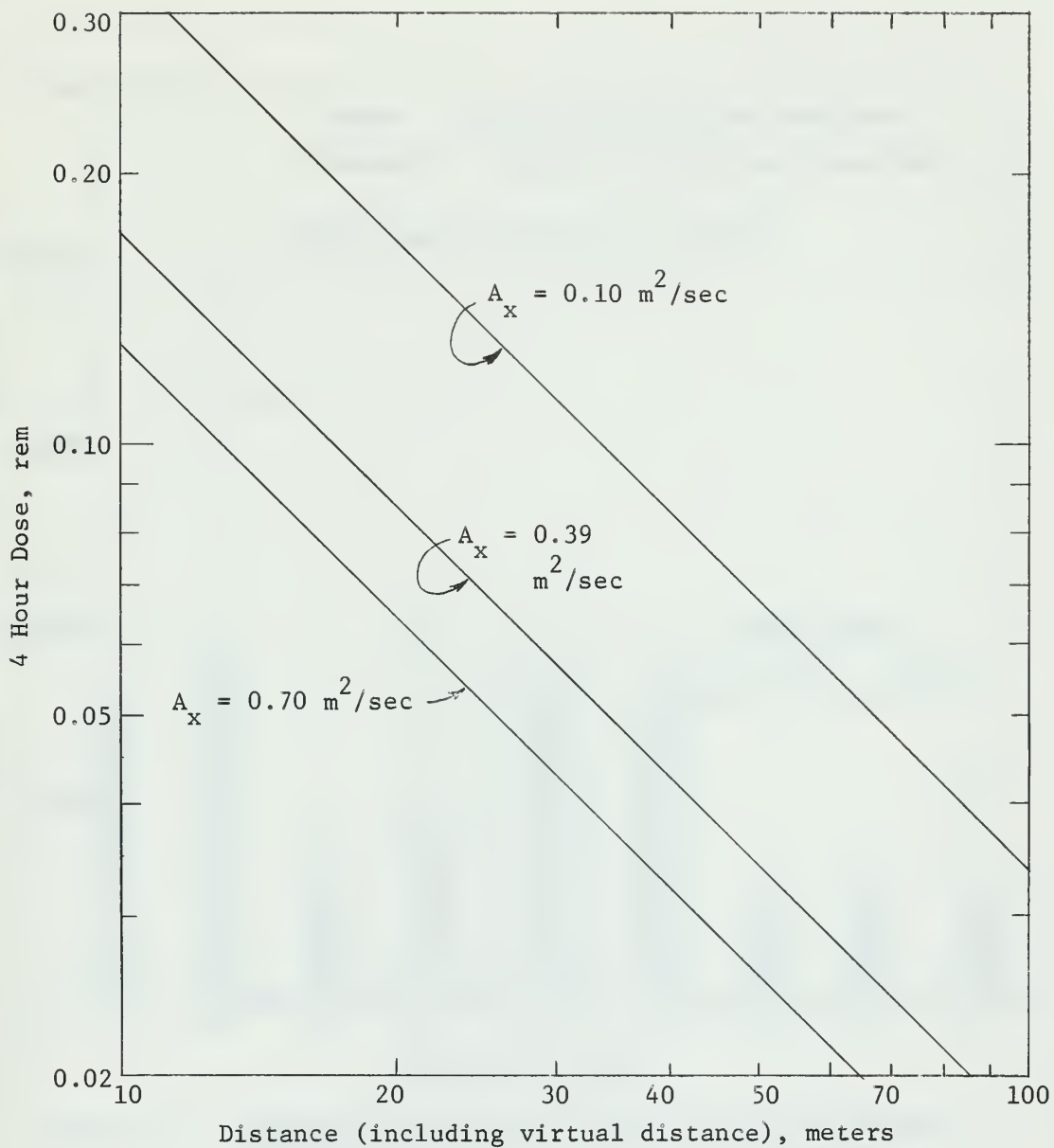
Figure 22. Effect of Variation of Horizontal Diffusion Coefficient, A_x, on 4 Hour Dose for a Contained 10 MW(t) Reactor
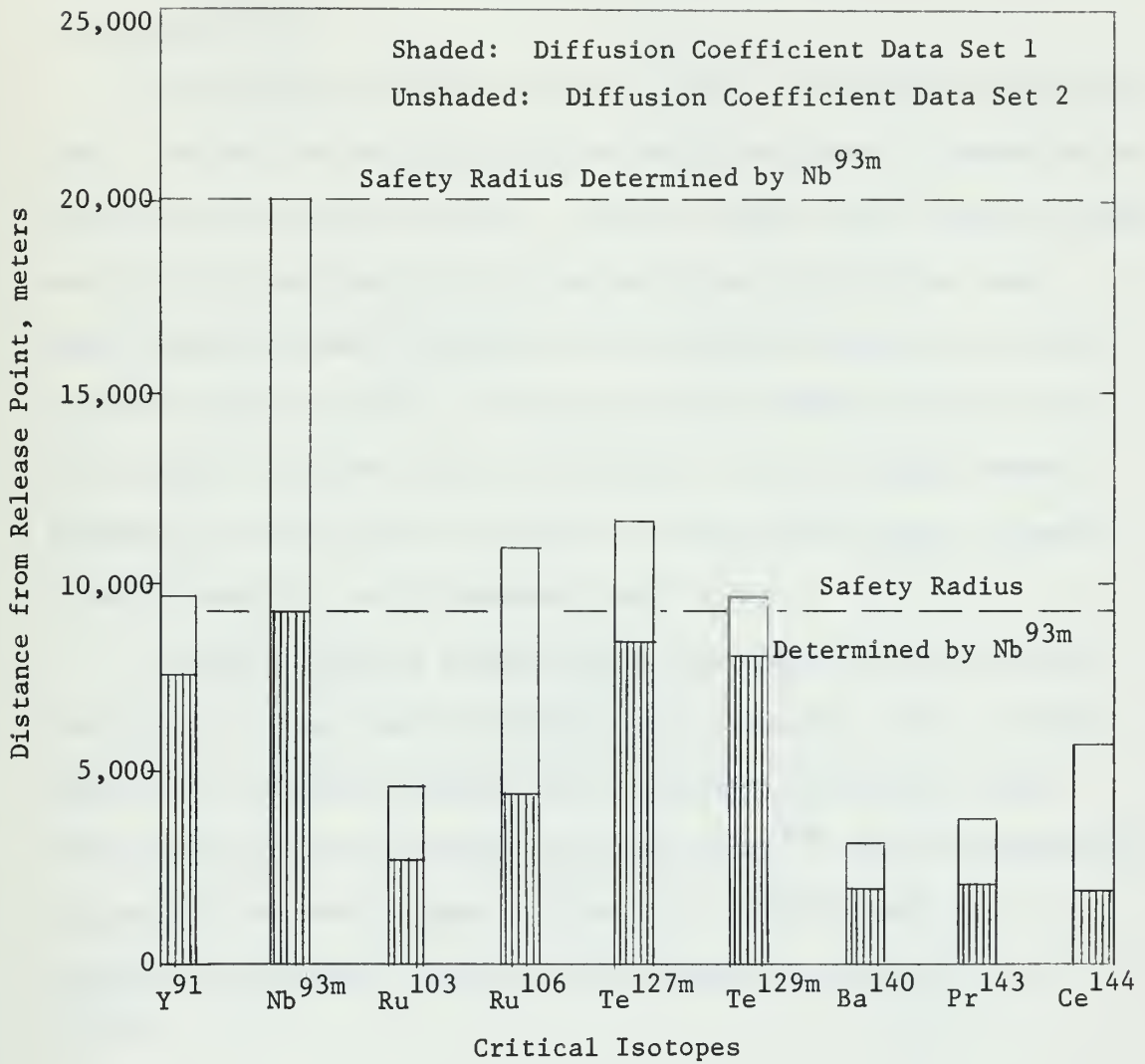
Figure 23. Distances Required for Concentration of Critical
Isotopes to Fall Below MPCC for a Contained
10 MW(t) Reactor

release inventory for Nb^{93m} is only 75 curies per megawatt because of its insolubility.

An examination of the critical isotope information contained in Table 6 points out the difficulty in making any general remarks as to what makes an isotope critical. The only common factor among the nine most critical isotopes is the relatively long half life of each. Other than this, the criticality of an isotope depends upon the MPCC and the release inventory. These quantities depend upon one or more of a number of factors such as solubility, critical organ, natural abundance of the carrier in seawater, concentration factor, fission product inventory, and permissible body burden.

The most critical isotope which determines the safety radius varies with release conditions and ocean parameters. For a 10 MW(t) reactor, the critical isotope for a contained system with a mean current velocity of one meter per second is Nb^{93m}; for an uncontained system with the same current profile it is Te^{129m}; while for a contained system and a current of two meters per second, it is Te^{127m}.

Table 6.   Critical Isotope Information

Isotope	Half Life (hrs)	Critical Organ	Carrier	Abundance of Carrier in Seawater (gr/kg)	Concentration Factor	Release Inventory (curies/MW)
Y^{91}	1,390	Bone	RE	3×10^{-5}	1,000	$\boxed{51,000}$
Nb^{93m}	32,400	Bone	Nb	$\boxed{1 \times 10^{-8}}$	200	75
Ru^{103}	984	GI(S)	Mn	2×10^{-6}	$\boxed{50,000}$	246
Ru^{106}	8,760	GI(LLI)	Mn	2×10^{-6}	$\boxed{50,000}$	15
Te^{127m}	2,160	Testis	Te	$\boxed{8 \times 10^{-8}}$	100	3
Te^{129m}	792	Testis	Te	$\boxed{8 \times 10^{-8}}$	100	29
Ba^{140}	307	GI(LLI)	Ba	3×10^{-5}	500	$\boxed{54,000}$
Pr^{143}	329	GI(LLI)	RE	3×10^{-5}	1,000	$\boxed{52,100}$
Ce^{144}	6,960	GI(LLI)	Ce	4×10^{-7}	1,000	292

Note: Item enclosed by box is considered to be factor which, in addition to long half life, has most effect on making isotope "critical."

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

Use of the computer program SEADIF allows a preliminary investigation of the suitability of an undersea site for a nuclear reactor in so far as radiation hazards are concerned. Results show the desirability of containment not so much because of the direct gamma radiation hazard but rather because of the possibility that exists for contaminating the marine biota in a large ocean area. With proper containment, the direct radiation hazard is essentially eliminated and the ocean area which could possibly be contaminated is minimized.

The models developed for both the contained and uncontained reactor systems are conservative. This conservative approach was taken at every step in the development of these models with the end result that figures for the exclusion radius, low population radius, and safety radius more nearly provide maximum hypothetical limits rather than good engineering estimates. A great deal of work remains to be done to refine these models.

Ocean Zone I was defined and then largely avoided because of the complex environment and range of conditions that exist. A more detailed study of this zone is required with particular emphasis on tidal effects, estuarine conditions, shore line contamination, and descriptive parameters in order to meaningfully apply the diffusion models. This zone will require further subdivision and the effects of vertical mixing and surface reflection will have to be considered.

For all the ocean zones, a need exists for realistic diffusion

and shear coefficients. Recent work by the Chesapeake Bay Institute[31,32,33] is a step in the right direction but much more study and experimentation is required.

Closely allied with diffusion coefficients is the effect of current variance. An extremely conservative assumption that was made was to assume no current variance. Incorporating the effects of such variance, particularly when dealing with the safety radius, would result in much more realistic conditions.

The assumptions involved in the determination of the fission product release inventory are based on the best information available with the desire for conservatism uppermost in mind. Much needs to be done in determining the amount of fission products that would be released to the marine environment in the event of a MHA. The solubility of fission products in seawater should be investigated, as should the chemical and physical processes involved in the removal of fission products by precipitation, adhesion, absorption, and uptake by the marine life.

Safety radius determinations have led to the identification of a number of critical isotopes. Starting with the isotopes of yttrium, niobium, ruthenium, tellurium, cesium, barium, and praseodymium a review of the input data used in calculating MPCC's should be made. More suitable carriers may be identified and more realistic concentration factors may be applicable. Marine biological assimilation and elimination rates should be investigated. Both the specific activity method and the concentration factor method of calculating MPCC's have shortcomings. A thorough study in this area could be of great benefit.

Contamination of the marine environment by activation products was not discussed. Corrosion products such as isotopes of iron, zinc, cobalt, manganese, chromium, copper, and nickel may be of particular interest as these elements have an extremely low natural abundance in seawater and high concentration factors in seafood.

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APPENDIX A

LIST OF SYMBOLS AND ABBREVIATIONS

A_c = effective cross sectional area of diffusion cloud, meters

A_x = eddy diffusivity in the x-direction, m^2/sec

A_y = eddy diffusivity in the y-direction, m^2/sec

A_z = eddy diffusivity in the z-direction, m^2/sec

A_1 = buildup coefficient

A_2 = buildup coefficient

B = biological decay constant of the carrier element for man, $days^{-1}$

D = dose rate, rem/hour

D = ocean depth, meters

d = containment diameter, meters

decomp = decomposes in cold water

E = energy per gamma photon, Mev

$\bar{E}_n$ = average gamma energy of the nth energy group, Mev

Erf z = error function defined as $\dfrac{2}{\sqrt{\pi}} \displaystyle\int_0^z e^{-t^2}\, dt$

Erfc z = complimentary error function = $1 - $ Erf z

F = ratio of consumption of water to consumption of seafood

f = concentration factor of seafood

I = total dose received, rem

I_{nb} = total quantity of the carrier in the critical organ, grams

I_{ns} = concentration of the carrier in the edible portions of seafood, grams/kg

I_{nw} = concentration of carrier in seawater, gram/kg

insol = insoluble in cold water

k = normalization constant for decay of mixed fission products, 3.981×10^3 $sec^{1.2}$

ℓ = leak rate, sec^{-1}

M = total activity of mixed fission products released to containment, curies

M_i = total activity of isotope i, released to containment, curies

M_n = activity of mixed fission products released to containment falling into the n-th gamma energy group, curies

MHA = maximum hypothetical accident

MPC = maximum permissible concentration in drinking water for 168 hour week, $\mu c/kg$

MPCC = maximum permissible concentration in seawater, $\mu c/kg$

q = maximum permissible quantity of radioisotope in the critical organ, μc

R = roentgen

S = factor to relate the recommendation for industrial workers to the civilian population, equal to $\frac{1}{10}$

S = concentration, $\mu c/kg$

S_i = concentration of a specific isotope i, $\mu c/kg$

S_p = peak concentration, $\mu c/kg$

T = time after release, sec

t = time, seconds

t_o = time (dummy variable)

V = virtual distance, meters

v_o = mean horizontal current velocity, meters/sec

x $\qquad$ = distance measured from peak concentration parallel to mean current flow, meters

x_0 $\qquad$ = distance measured from initial point of release

y $\qquad$ = distance normal to mean current flow, parallel to ocean floor, measured from point of release, meters

z $\qquad$ = distance above ocean floor (point of release), meters

α $\qquad$ = diffusion term, $\sec^{-3/2}$ per meter^3

α_1 $\qquad$ = buildup coefficient

α_2 $\qquad$ = buildup coefficient

β $\qquad$ = diffusion-shear term, $\sec^{-1}$

$\Gamma(z)$ $\qquad$ = gamma function defined as $\displaystyle\int_0^\infty t^{z-1} e^{-t} \, dt$

Γ $\qquad$ = gamma energy group

$\gamma(a,x)$ $\qquad$ = incomplete gamma function defined as $\displaystyle\int_0^x e^{-t} t^{a-1} \, dt$

$\delta(x)$ $\qquad$ = delta function defined to be zero for all values of x except x = 0

ε_n $\qquad$ = energy coefficient for n^{th} energy group, R-meters^3

κ $\qquad$ = energy dependent conversion coefficient, R/hr per $\text{Mev/cm}^2\text{-sec}$

λ $\qquad$ = physical decay constant of the radioisotope

μ $\qquad$ = absorption coefficient, cm^{-1}

σ $\qquad$ = mean standard deviation of cloud, meters

τ $\qquad$ = irradiation time, sec

ϕ $\qquad$ = gamma flux, $\text{photons/cm}^2\text{-sec}$

Ω_y $\qquad$ = $\dfrac{dv}{dy}$ = horizontal shear, $\sec^{-1}$

Ω_z $\qquad$ = $\dfrac{dv}{dz}$ = vertical shear, $\sec^{-1}$

Superscript prime (') indicates applicability to cases where radiological decay is considered

APPENDIX B

DERIVATION OF EQUATIONS

1. Concentration of a Single Isotope (Instantaneous Release)

Figure B-1 illustrates a diffusing cloud of fission products moving with a mean current velocity v_0. At a time t after release, the cloud is carried a distance equal to $v_0 t$. During this time, diffusion and shear effects are causing the cloud to spread and elongate. The basic equation for a coordinate system moving with a mean current velocity v_0 is

$$\frac{\partial S}{\partial t} - (\Omega_y \, y + \Omega_z z) \frac{\partial S}{\partial x} = A_x \frac{\partial^2 S}{\partial x^2} + A_y \frac{\partial^2 S}{\partial y^2} + A_z \frac{\partial^2 S}{\partial z^2} \quad . \qquad (B1.1)$$

Equation (B1.1) is a mass balance of the radioisotope concentration with neither production nor absorption (losses). The terms on the right hand side describe the net leakage of the radioisotopes into a unit volume due to diffusion. The second term on the left represents net leakage into a unit volume due to a non-uniform mean velocity (shear effect).

With an initial condition

$$S_i(0,x,y,z) = M_i \, \delta(x) \, \delta(y) \, \delta(z), \qquad (B1.2)$$

which describes the instantaneous release of the fission product release inventory for a single isotope of activity M_i from a point source placed at x=y=z=0, Carter and Okubo[23] have obtained the following solution for infinite space:
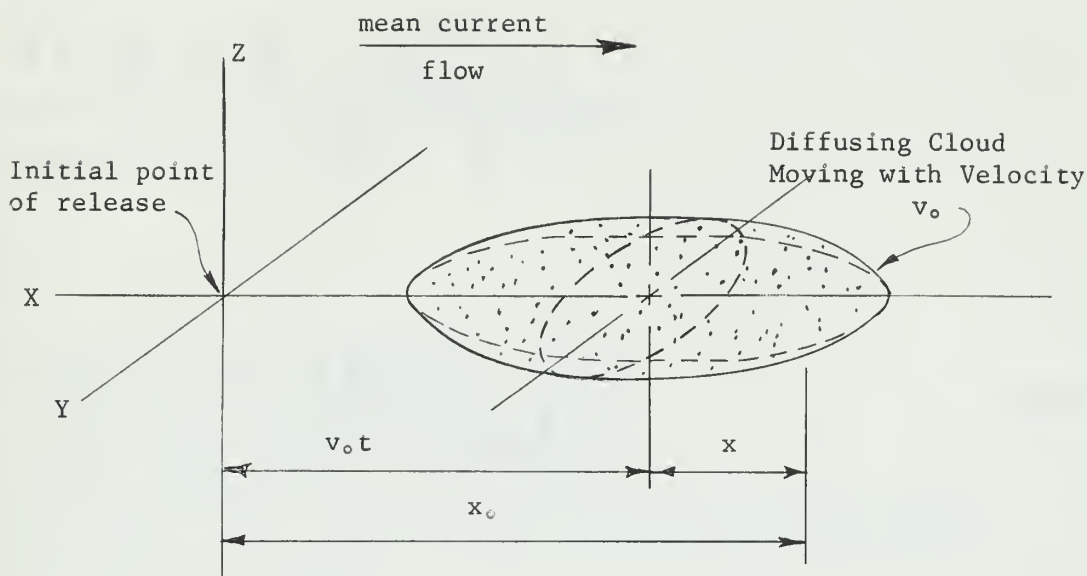
Figure B-1. Coordinate System Relationships

$$S_i(t,x,y,z) = \frac{M_i}{8\pi^{3/2}(A_x A_y A_z)^{1/2} \; t^{3/2} \; \sqrt{1 + \frac{1}{12}(\Omega_y^2 \frac{A_y}{A_x} + \Omega_z^2 \frac{A_z}{A_x})t^2}}$$

$$\exp - \left[\frac{x^2}{4A_x t \left[1 + \frac{1}{12}(\Omega_y^2 \frac{A_y}{A_x} + \Omega_z^2 \frac{A_z}{A_y}) \, t^2\right]} \right.$$

$$\left. + \frac{1 + (\frac{1}{3}\Omega_y^2 \frac{A_y}{A_x} + \frac{1}{12}\Omega_z^2 \frac{A_z}{A_x}) \, t^2}{4A_x t \left[1 + \frac{1}{12}(\Omega_y^2 \frac{A_y}{A_x} + \Omega_z^2 \frac{A_z}{A_x})t^2\right]} \; y^2 \right.$$

$$+ \frac{1 + (\frac{1}{12} \ \Omega_y^2 \ \frac{A_y}{A_x} + \frac{1}{3} \Omega_z^2 \ \frac{A_z}{A_x}) \ t^2}{4A_x t \left[1 + \frac{1}{12} \ (\Omega_y^2 \ \frac{A_y}{A_x} + \Omega_z^2 \ \frac{A_z}{A_x}) \ t^2\right]} \ z^2$$

$$\left. \frac{t(\Omega_y y + \Omega_z z)x + \frac{1}{2} \Omega_y \Omega_z t^2 yz}{4A_x t \left[1 + \frac{1}{12} \ (\Omega_y^2 \ \frac{A_y}{A_x} + \Omega_z^2 \ \frac{A_z}{A_x}) t^2\right]} \right] . \tag{B1.3}$$

The concentration of the center of the cloud ($x = y = z = 0$) is given by

$$S_p(t) \ = \ \frac{M_i}{8\pi^{3/2} \ (A_x A_y A_z)^{1/2} \ t^{3/2} \ \sqrt{1 + \frac{1}{12}(\Omega_y^2 \ \frac{A_y}{A_x} + \Omega_z^2 \ \frac{A_z}{A_x}) t^2}} \tag{B1.4}$$

If the orientation of the X-axis is in the direction of the mean current flow, the concentration as a function of distance along this axis is given as

$$S_i(t,x) \ = \ \frac{M_i \alpha}{t^{3/2} \ \sqrt{1 + \beta t^2}} \ \exp - \left[\frac{x^2}{4A_x t \ (1 + \beta t^2)}\right], \tag{B1.5}$$

where

$$\alpha = \frac{1}{8\pi^{3/2} (A_x A_y A_z)^{1/2}} , \qquad (B1.6)$$

and

$$\beta = \frac{1}{12}(\Omega_y^2 \frac{A_y}{A_x} + \Omega_z^2 \frac{A_z}{A_x}) . \qquad (B1.7)$$

Substituting $x = x_0 - v_0 t$ into Equation (B1.5), the following equation may be written:

$$S_i(t,x) = \frac{M_i \alpha}{t^{3/2} \sqrt{1 + \beta t^2}} \exp - \left[\frac{(x_0 - v_0 t)^2}{4A_x t (1 + \beta t^2)} \right]. \qquad (B1.8)$$

It is possible to compute from this equation the concentration of a specific isotope at a distance x_0 measured parallel to the direction of mean current flow for an instantaneous release of an isotope of activity M_i. Radioactive decay has not been considered.

2. Dose Rate for Instantaneous Release (without decay)

The dose rate is a function of the gamma flux at the point in question. Water has excellent shielding properties and because of the high attenuation of the gamma flux, contributions from more than a few meters away are negligible. Therefore, it is reasonable to make the simplifying assumption that at the point in question there exists an essentially infinite cloud of uniform concentration.

A person in the water at a distance x_o, in the center ($x=0$) of this infinite cloud of uniform concentration $S(x_o)$, is exposed to a gamma flux as given by Equation (B2.1).

$$\phi(x_o,t) = \int_{vol.} \frac{S(x_o,t)e^{-\mu r}}{4\pi r^2} (A_1 e^{-\alpha_1 \mu r} + A_2 e^{-\alpha_2 \mu r})dV. \qquad (B2.1)$$

Equation (B2.1) comes directly from the fact that the gamma flux from an isotropic point source (a volume element dV of concentration S) located at a distance r is

$$\frac{S\ e^{-\mu r}\ dV}{4\pi r^2} .$$

For an infinite cloud, the total flux will be equal to the gamma flux due to the volume element integrated over the entire volume. The term $(A_1\ e^{-\alpha_1 \mu r} + A_2\ e^{-\alpha_2 \mu r})$ represents the buildup factor. Values for the parameters A_1, A_2, α_1, and α_2 are given by Rockwell[24] and are presented in Table B-1. Integrating Equation (B2.1) over the solid angle

$$\phi(x_o,t) = S(x_o,t) \int_o^\infty \left[A_1 e^{-\mu(1+\alpha_1)r} + A_2 e^{-\mu(1+\alpha_2)r} \right] dr, \qquad (B2.2)$$

Table B-1.   Source Term Coefficients for 7 Group Spectrum

GROUP	ENERGY INTERVAL	$\bar{E}$ Mev	Dose Build-up Factors for Water				μ_s cm^{-1}	$\kappa(E)$ R/hr per Mev/cm^2-sec	ϵ_n Rm^3
			A_1	A_2	α_1	α_2			
Γ_1	.1- .4	0.25	See note (1)				0.125	1.92×10^{-6}	4.30×10^{-15}
Γ_2	.4- .9	0.65	18.0	-17.0	-0.125	0.0	0.086	1.97×10^{-6}	1.46×10^{-14}
Γ_3	.9-1.35	1.12	10.0	- 9.0	-0.100	0.048	0.066	1.84×10^{-6}	2.04×10^{-14}
Γ_4	1.35-1.80	1.58	8.5	- 7.5	-0.085	0.080	0.056	1.72×10^{-6}	3.17×10^{-14}
Γ_5	1. 8-2.2	2.00	7.5	- 6.5	-0.076	0.094	0.049	1.60×10^{-6}	2.05×10^{-14}
Γ_6	2..2-2.6	2.40	5.8	- 4.8	-0.067	0.101	0.045	1.52×10^{-6}	4.17×10^{-14}
Γ_7	>2.6	3.00	5.2	- 4.2	-0.062	0.108	0.040	1.43×10^{-6}	5.26×10^{-14}

(1) For Γ_1 assume buildup factor is equal to 1 and use $\mu_a = 0.031$ cm^{-1}. Then

$$\epsilon_1 = \frac{k_1 \bar{E}}{\mu_a} = \frac{(1.92 \times 10^{-6})(.25)}{(0.031)} = 1.55 \times 10^{-5} \ \frac{R \ cm^3}{hr} \ sec = 4.30 \times 10^{-15} \ Rm^3$$

$$\phi(x_\circ, t) = S(x_\circ, t) \left[\frac{A_1}{\mu(1+\alpha_1)} + \frac{A_2}{\mu(1+\alpha_2)} \right], \qquad (B2.3)$$

where ϕ, S, μ, A_1, A_2, α_1, and α_2 are energy dependent. The dose rate in rem per hour for an RBE of 1 due to this concentration is equal to the product of the average energy of the gamma photons, the gamma flux, and an energy dependent conversion coefficient.

$$D(E, x_\circ, t) = \kappa(E) \, E \, \phi(E, x_\circ, t). \qquad (B2.4)$$

Substituting Equation (B2.3)

$$D(E, x_\circ, t) = \kappa(E) \, E \, S(E, x_\circ, t) \left[\frac{A_1(E)}{\mu(E) \, (1+\alpha_1(E))} + \frac{A_2(E)}{\mu(E) \, (1+\alpha_2(E))} \right]. \qquad (B2.5)$$

If an energy coefficient, ε_n, is defined by the following equation

$$\varepsilon_n = \kappa(\overline{E}) \, \overline{E}_n \left[\frac{A_1(\overline{E})}{\mu(\overline{E})(1+\alpha_1(\overline{E}))} + \frac{A_2(\overline{E})}{\mu(\overline{E})(1+\alpha_2(\overline{E}))} \right] \qquad (B2.6)$$

where $\overline{E}_n$ represents the average energy of the nth energy group of a seven group discrete gamma spectrum, then the dose rate due to the entire fission product release inventory is

$$D(t,x_o) = \frac{\left\{ \displaystyle\sum_{n=1}^{7} \varepsilon_n M_n \right\} \alpha}{t^{3/2} \sqrt{1 + \beta t^2}} \quad \exp - \left[\frac{(x_o - v_o t)^2}{4A_x t (1 + \beta t^2)} \right]. \tag{B2.7}$$

3. Total Dose for Instantaneous Release (without decay)

The determining factor in establishing the exclusion radius is the total dose I which is received over a period of time from $t = 0$ to $t = T$ where T is the time required for evacuation of personnel from the area. The total dose may be determined from

$$I(x_o) = \int_{0}^{T} D(t,x_o)dt, \tag{B3.1}$$

$$I(x_o) = \left\{ \sum_{n=1}^{7} \varepsilon_n M_n \right\} \alpha \int_{0}^{T} \frac{1}{t^{3/2} \sqrt{1+\beta t^2}} \quad \exp- \left[\frac{(x_o - v_o t)^2}{4A_x t(1+\beta t^2)} \right] dt. \tag{B3.2}$$

For determining the low population radius, the applicable equation is

$$I(x_o) = \left\{ \sum_{n=1}^{7} \varepsilon_n M_n \right\} \alpha \int_{0}^{\infty} \frac{1}{t^{3/2} \sqrt{1 + \beta t^2}} \exp - \left[\frac{(x_o - v_o t)^2}{4A_x t(1+\beta t^2)} \right] dt \tag{B3.3}$$

where the upper limit is taken as infinity.

Equation (B3.2) is best suited for computer solution by numerical techniques. An analytical solution is possible for the case where the current velocity is zero. For $v_0 = 0$, Equation (B3.2) becomes

$$I(x_0) = \left\{ \sum_{n=1}^{7} \varepsilon_n M_n \right\} \alpha \int_0^T \frac{1}{t^{3/2}\sqrt{1+\beta t^2}} \exp - \left[\frac{x_0^2}{4A_x t(1+\beta t^2)} \right] dt.$$

$$(B3.4)$$

For $t \ll \beta^{-1/2}$, $(\beta^{-1/2} \approx 8$ hours for typical diffusion coefficients$)$

$$I(x_0) = \left\{ \sum_{n=1}^{7} \varepsilon_n M_n \right\} \alpha \int_0^T t^{-3/2} \exp - \left[\frac{x_0^2}{4A_x t} \right] dt. \qquad (B3.5)$$

Substituting $\theta = x_0^2 /4A_x$ and $u = \theta/t$; $du = -(\theta/t^2)dt$

$$I(x_0) = \left\{ \sum_{n=1}^{7} \varepsilon_n M_n \right\} \alpha \int_{\theta/T}^{\infty} \left(\frac{u}{\theta} \right)^{3/2} (e^{-u}) \frac{\theta}{u^2} du$$

$$I(x_0) = \left\{ \sum_{n=1}^{7} \varepsilon_n M_n \right\} \alpha \; \theta^{-1/2} \int_{\theta/T}^{\infty} u^{-1/2} e^{-u} du.$$

This is a form of the incomplete gamma function.

$$I(x_o) = \left\{ \sum_{n=1}^{7} \epsilon_n M_n \right\} \alpha \, \theta^{-1/2} \, \Gamma(\tfrac{1}{2}, \, \theta/T),$$

$$= \left\{ \sum_{n=1}^{7} \epsilon_n M_n \right\} \alpha \, \theta^{-1/2} \left[\Gamma(\tfrac{1}{2}) - \gamma(\tfrac{1}{2}, \, \tfrac{\theta}{T}) \right],$$

$$= \left\{ \sum_{n=1}^{7} \epsilon_n M_n \right\} \alpha \, \theta^{-1/2} \left[\sqrt{\pi} - \sqrt{\pi} \, \text{Erf} \, \sqrt{\tfrac{\theta}{T}} \right],$$

$$= \left\{ \sum_{n=1}^{7} \epsilon_n M_n \right\} \alpha \, \theta^{-1/2} \, \sqrt{\pi} \, \text{Erfc} \, \sqrt{\theta/T} \quad ,$$

or

$$I(x_o) = \frac{2\sqrt{A_x \pi} \; \alpha \left\{ \sum_{n=1}^{7} \epsilon_n M_n \right\}}{x} \; \text{Erfc} \; \frac{x}{2\sqrt{A_x T}} . \tag{B3.6}$$

4. Summary − Instantaneous Release without Decay

The preceding equations have been derived from Carter and Okubo's solution in infinite space. No allowance has been made for the reflective boundary effect of the ocean floor. As the application for which these equations are intended deals with locations at or only slightly above the ocean floor, an approximate solution

may be obtained by multiplying Equation (B1.3) by two, i.e., adding the image with respect to the ocean floor.[23] The equations below include this factor of two.

Concentration of a specific isotope i;

$$S_i(t,x_o,v_o) = \frac{2\,M_i\alpha}{t^{3/2}\sqrt{1+\beta t^2}} \quad \exp - \frac{(x_o - v_o t)^2}{4A_x t(1+\beta t^2)} \,. \tag{B4.1}$$

Concentration of a specific isotope i at a time $t \ll \beta^{-1/2}$;

$$S_i(t,x_o,v_o) = 2M_i\alpha t^{-3/2} \exp - \frac{(x_o - v_o t)^2}{4A_x t} \,. \tag{B4.2}$$

Concentration of a specific isotope i at a time $t \gg \beta^{-1/2}$;

$$S_i(t,x_o,v_o) = \frac{2M_i\alpha}{t^{5/2}\sqrt{\beta}} \exp - \frac{(x_o - v_o t)^2}{4A_x\beta t^3} \,. \tag{B4.3}$$

Dose rate due to the total fission product release inventory;

$$D(t,x_o,v_o) = \frac{2\left\{\sum_{n=1}^{7}\varepsilon_n M_n\right\}\alpha}{t^{3/2}\sqrt{1+\beta t^2}} \exp - \frac{(x_o - v_o t)^2}{4A_x t(1+\beta t^2)} \tag{B4.4}$$

Four hour total direct gamma dose;

$$I(x_o,v_o) = \int_{0}^{T=4\text{ hr}} D(t,x_o,v_o)dt \tag{B4.5}$$

Total dose approximation for zero current velocity;

$$I(x_0) = \frac{\sum_{n=1}^{7} \varepsilon_n M_n}{2\pi(A_y A_z)^{1/2} x} \; Erfc \; \frac{x}{2\sqrt{A_x T}} \; . \tag{B4.6}$$

5. Decay of Fission Products[25,26]

It is possible to express the rate of decay of the complex fission product mixture for the period of time from about 10 seconds to several weeks after shutdown as approximately equal to $kt^{-1.2}$. Certainly for times greater than 10^3 seconds, this approximation is conservative as shown by Figure B-2. The following assumptions are made:

    (1) The fission product release inventory decays at the same rate as the gross fission product inventory.

    (2) Only fission products with a half life greater than 240 seconds are included in the mixed fission product release inventory.

    (3) No decay of fission products occurs until after 1000 seconds after shutdown.

    (4) After 1000 seconds after shutdown, the mixed fission product inventory decays as $kt^{-1.2}$.

Then the decay of the fission product release inventory is written as follows:

$$M' = M \qquad \text{for } t < 10^3 \text{ seconds,}$$
$$M' = M k t^{-1.2} \qquad \text{for } t > 10^3 \text{ seconds.} \tag{B5.1}$$

6. Instantaneous Release with Decay

If $\psi(t,x_0,v_0)$ is defined by Equation (B6.1) as
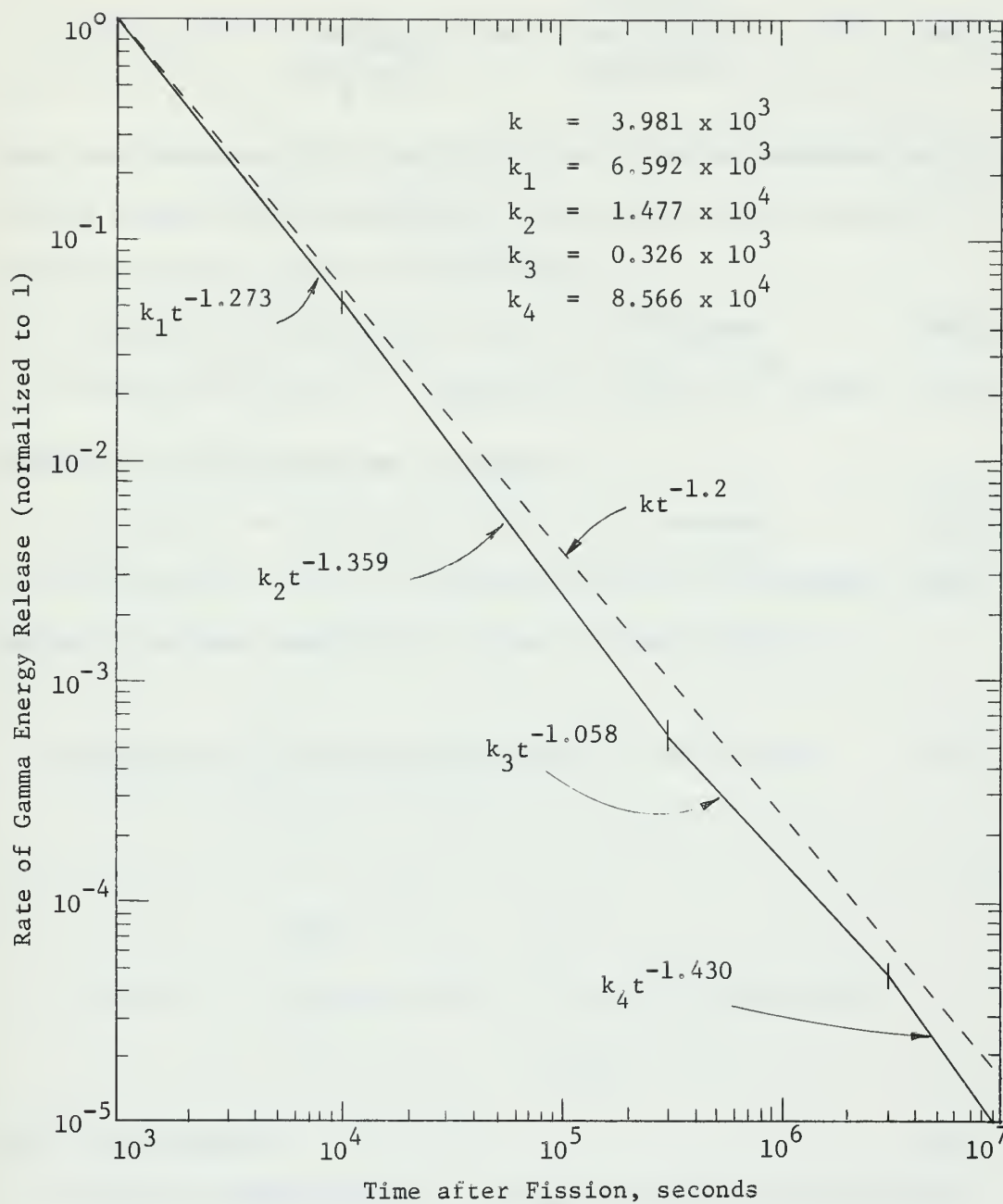
Figure B-2.   Empirical Equations for Rate of Gamma Energy
Release Following Fission (Data from
Foderaro[25])

$$\psi(t,x_o,v_o) = \frac{2\alpha}{t^{3/2}\sqrt{1+\beta t^2}} \exp - \frac{(x_o-v_o t)^2}{4A_x t(1+\beta t^2)} \tag{B6.1}$$

then from Equations (B4.1) and (B5.1) the following equations may be written to give the concentration for the total fission product release inventory at time t after release:

$$S'(t,x_o,v_o) = M\,\psi(t,x_o,v_o) \quad \text{for } t < 10^3 \text{ seconds} \tag{B6.2}$$

$$S'(t,x_o,v_o) = M\,k\,t^{-1.2}\,\psi(t,x_o,v_o) \quad \text{for } t > 10^3 \text{ seconds} \tag{B6.3}$$

Similarly, the dose rate may be given as

$$D'(t,x_o,v_o) = D(t,x_o,v_o), \quad \text{for } t < 10^3 \text{ seconds,} \tag{B6.4}$$

$$D'(t,x_o,v_o) = k\,t^{-1.2}\,D(t,x_o,v_o), \quad \text{for } t > 10^3 \text{ seconds} \tag{B6.5}$$

And the total dose received up to time T after release is

$$I'(x_o,v_o) = \int_o^T D(t,x_o,v_o)dt, \quad \text{for } T < 10^3 \text{ seconds} \tag{B6.6}$$

$$I'(x_o,v_o) = \int_o^{10^3} D(t,x_o,v_o)dt \; + \; \int_{10^3}^T k\,t^{-1.2}\,D(t,x_o,v_o)dt,$$

for $T > 10^3$ seconds. $\tag{B6.7}$

When the concentration of a specific isotope is investigated, the appropriate decay constant λ_i must be used rather than Equation (B5.1) since Equation (B5.1) is valid only when considering the entire mixed fission product inventory. For a specific isotope

$$S'_i(t,x_o,v_o) = M_i e^{-\lambda_i t}\psi(t,x_o,v_o), \quad \text{for all } t > 0. \tag{B6.8}$$

From Equation (B1.4) it may be seen that the peak concentration will be given by

$$S_p'(t) = \frac{M_i \, \alpha \, e^{-\lambda_i t}}{t^{3/2}\sqrt{1+\beta t^2}} \qquad (B6.9)$$

when decay is considered. If $S'_p(t)$ is set equal to the applicable MPCC, Equation (B6.9) may be rearranged as follows:

$$(\beta t^5 + t^3) \, e^{2\lambda_i t} = \left(\frac{M_i \alpha}{MPCC}\right)^2 . \qquad (B6.10)$$

Solution of Equation (B6.10) will give the time at which the peak concentration will equal MPCC.

7. <u>Continuous Release (without decay)</u>

For the instantaneous release of an amount $M\ell$ (where M is the fission product release inventory at t=0 and ℓ is the leak rate from the containment), the concentration along the X-axis will be

$$S(t,x_o,v_o) = \int_o^t \frac{2M\ell}{t_o^{3/2}\sqrt{1+\beta t_o}^2}\left[\exp - \frac{(x_o - v_o t_o)^2}{4A_x t_o (1+\beta t_o^2)}\right] dt_o \qquad (B7.1)$$

or substituting Equation (B6.1)

$$S(t,x_o,v_o) = \int_o^t M\ell \psi(t_o,x_o,v_o)dt_o \qquad (B7.2)$$

For a given distance greater than zero, the concentration will be initially equal to zero. If the leak rate is held constant and neither depletion of the gross fission product inventory nor

radiological decay is considered (both conservative factors), then after a period of time, a steady state value for the concentration will be achieved. This steady state value may be achieved by setting the upper limit of Equation (B7.2) equal to infinity, or

$$S(x_o, v_o) = \int_0^\infty M \ell \psi(t_o, x_o, v_o) dt_o \ .$$

(B7.3)

The dose rate will be

$$D(x_o, v_o) = \left\{ \sum_{n=1}^{7} \epsilon_n M_n \right\} \ell \int_0^\infty \psi(t_o, x_o, v_o) dt_o \ .$$

(B7.4)

For steady state conditions, the total dose received will simply be the product of the dose rate and the time, or

$$I(x_o, v_o) = \left\{ \sum_{n=1}^{7} \epsilon_n M_n \right\} \ell \ T \int_0^\infty \psi(t_o, x_o, v_o) dt_o$$

(B7.5)

where T = 4 hours for exclusion radius determinations.

8. Continuous Release (with decay)

The equations developed in the preceding section are based on two very conservative assumptions:

(1) steady state conditions are achieved instantaneously, and

(2) radiological decay is ignored.

In the case of high velocity currents and relatively short distances, actual conditions closely approximate the first assumption. Because of this and the fact that such an assumption simplifies

computer calculations, it is desirable to retain this assumption and base the following equations on the steady state results.

If decay is considered, the applicable equations at time t may be given as follows:

$$S_1'(x_o,v_o) = \int_0^\infty M\ell\psi(t_o,x_o,v_o)dt_o \quad , \quad \text{for } t < 10^3 \text{ seconds} \quad (B8.1)$$

$$S_2'(t,x_o,v_o) = M\ell kt^{-1.2} \int_0^\infty \psi(t_o,x_o,v_o)dt_o \text{ , for } t > 10^3 \text{ seconds} \quad (B8.2)$$

$$S_i'(t,x_o,v_o) = M\ell e^{-\lambda_i t} \int_0^\infty \psi(t_o,x_o,v_o)dt_o, \text{ for a specific isotope}$$

and all $t \geq 0$

$$(B8.3)$$

$$D_1'(x_o,v_o) = \left\{\sum_{n=1}^7 \varepsilon_n M_n\right\} \ell \int_0^\infty \psi(t_o,x_o,v_o)dt_o \text{ , for } t < 10^3$$

seconds,

$$(B8.4)$$

$$D_2'(t,x_o,v_o) = \left\{\sum_{n=1}^7 \varepsilon_n M_n\right\} \ell kt^{-1.2} \int_0^\infty \psi(t_o,x_o,v_o)dt_o, \text{ for}$$

$t > 10^3$ seconds,

$$(B8.5)$$

$$I_1'(t,x_o,v_o) = t\, D_1'(x_o,v_o), \text{ for } t < 10^3 \text{ seconds, and} \quad (B8.6)$$

$$I_2'(t,x_o,v_o) = (10^3 \text{ sec})D_1'(x_o,v_o) + D_1'(x_o,v_o)k \int_{10^3}^t t_o^{-1.2}dt_o,$$

for $t > 10^3$ seconds.

$$(B8.7)$$

The steady state concentration as a function of distance is shown in Figure B-3.
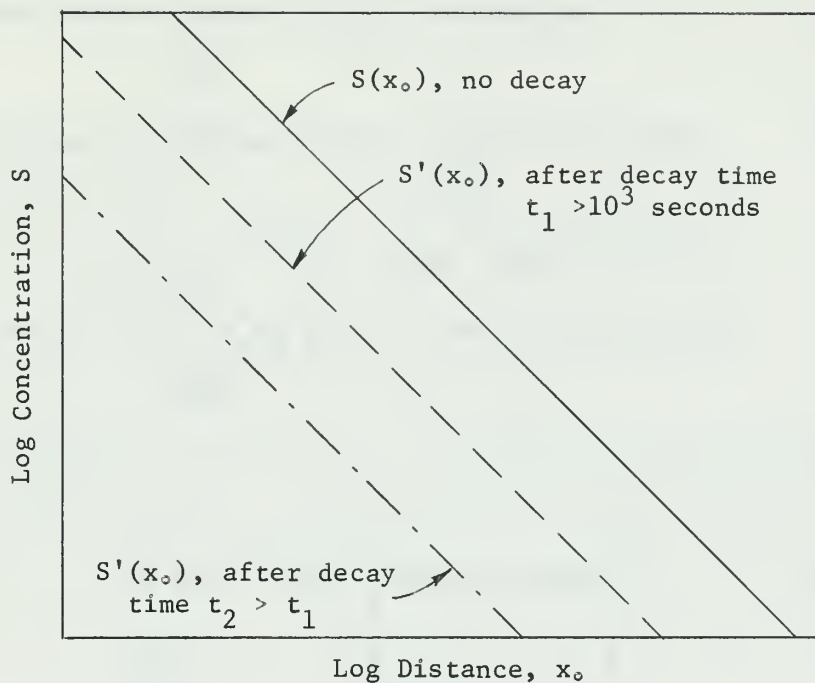
Figure B-3.   Concentration of Fission Products
as a Function of Distance

If the instantaneous steady state assumption is not used, the results may be summarized as follows for times after release t greater than 10^3 seconds:

$$S_2'(t,x_o,v_o) = M\ell k t^{-1.2} \int_o^t \psi(t_o,x_o,v_o)dt_o \tag{B8.8}$$

and

$$D_2'(t,x_o,v_o) = \left\{\sum_{n=1}^{7} \varepsilon_n M_n\right\} \ell k t^{-1.2} \int_o^t \psi(t_o,x_o,v_o)dt_o \tag{B8.9}$$

where S_2' and D_2' are the concentration and dose rate respectively at time t with radiological decay considered. The total dose received for exposure times in excess of 1000 seconds is

$$I_2'(t,x_\circ,v_\circ) = \int_\circ^{10^3} D_1'(x_\circ,v_\circ)dt_\circ + \int_{10^3}^{t} D_2'(t_\circ,x_\circ,v_\circ)dt_\circ \qquad (B8.10)$$

$$I_2'(t,x_\circ,v_\circ) = \left\{ \sum_{n=1}^{7} \varepsilon_n M_n \right\} \ell \left[\int_\circ^{10^3} dt_\circ \int_\circ^{10^3} \psi(t_\circ,x_\circ,v_\circ)dt_\circ \right.$$

$$\left. + \int_{10^3}^{t} kt_\circ^{-1.2} dt_\circ \int_0^{t} \psi(t_\circ,x_\circ,v_\circ)dt_\circ \right]. \qquad (B8.11)$$

9. <u>Continuous Release - Approximate Analytical Solution for $v_\circ=0$</u>

Factoring $D_1'(x_\circ,v_\circ)$ from Equation (B8.7) and substituting Equation (B8.4), it is possible to obtain, for $t > 10^3$ seconds,

$$I_2'(t,x_\circ,v_\circ) = \left[\left\{ \sum_{n=1}^{7} \varepsilon_n M_n \right\} \ell \int_\circ^{\infty} \psi(t_\circ,x_\circ,v_\circ)dt_\circ \right] \left[10^3 + k \int_{10^3}^{t} t_\circ^{-1.2}dt_\circ \right].$$

$$(B9.1)$$

Dividing the integral over $\psi(t_\circ,x_\circ,v_\circ)dt_\circ$ at $t_i = \beta^{-1/2}$ and rearranging terms

$$I_2'(t,x_o,v_o) = \left[10^3 + k \int_{10^3}^{t} t_o^{-1.2}\, dt_o\right]\left[\left\{\sum_{n=1}^{7} \varepsilon_n M_n\right\} \ell\right]$$

$$\left[\int_0^{t_i} \psi(t_o,x_o,v_o)\, dt_o + \int_{t_i}^{\infty} \psi(t_o,x_o,v_o)\, dt_o\right]. \qquad (B9.2)$$

Substituting Equation (B6.1) for ψ and making the approximation that for times less than t_i the term $(1+\beta t_o^2) \approx 1$ and that for times greater than t_i the term $(1+\beta t_o^2) \approx \beta t_o^2$ it is possible to obtain

$$I_2'(t,x_o,v_o) = \left[10^3 + k \int_{10^3}^{t} t_o^{-1.2}\, dt_o\right]\left[\left\{\sum_{n=1}^{7} \varepsilon_n M_n\right\} 2\ell\alpha\right]$$

$$\left[\int_0^{t_i} t_o^{-3/2} \exp{-\frac{(x_o-v_o t_o)^2}{4A_x t_o}}\, dt_o + \beta^{-1/2}\int_{t_i}^{\infty} t_o^{-5/2}\exp{-\frac{(x_o-v_o t_o)^2}{4A_x \beta t_o^3}}\, dt_o\right].$$

$$(B9.3)$$

For the case where $v_o=0$ and proceeding in a manner similar to Section 3, the following results are obtained:

$$I_2'(t,x_o) = \left[10^3 + 5k(10^{-0.6} - t^{-0.2})\right] \left[2\ell\alpha \sum_{n=1}^{7} \varepsilon_n M_n\right]$$

$$\left[\frac{2\sqrt{\pi A_x}}{x_o} \; \text{Erfc} \; \frac{x_o}{\sqrt{4A_x t_i}} + \frac{2\sqrt{\pi A_x}}{3x_o} \; \text{Erf} \; \frac{x_o}{\sqrt{4A_x \beta t_i^3}}\right].$$

$$I_2'(t,x_o) = \left[10^3 + 5k(10^{-0.6} - t^{-0.2})\right] \left[\frac{4\ell\alpha\sqrt{\pi A_x}}{x_o} \sum_{n=1}^{7} \varepsilon_n M_n\right]$$

$$\left[\text{Erfc} \; \frac{x_o}{2\sqrt{A_x t_i}} + \frac{1}{3} \; \text{Erf} \; \frac{x_o}{2\sqrt{A_x t_i}}\right]. \tag{B9.4}$$

10. Virtual Distance

A virtual distance concept is included in the computer solutions in order to examine distances very close to the containment. If the effective area of the diffusing cloud is defined as extending a distance of 3σ, where for small times, σ^2 is given by Carter and Okubo[23] as

$$\sigma_y^2 = 2A_y t, \tag{B10.1}$$

$$\sigma_z^2 = 2(A_x A_y)^{1/2} t, \tag{B10.2}$$

then the cross-sectional area of the cloud (Y-Z plane) may be approxi-

mated as

$$A_c = 9 \pi \sigma_y \sigma_z \quad , \qquad (B10.3)$$

$$A_c = 18 \pi t A_x^{.25} A_y^{.75} \quad . \qquad (B10.4)$$

If the area of the cloud is set equal to the area of the containment

the time required for the diffusion process to approximate actual

conditions will be given by

$$t = \frac{d^2}{72 A_x^{.25} A_y^{.75}} \quad , \qquad (B10.5)$$

or for a given current velocity, the virtual distance will be

$$V = v_o t \quad ,$$

$$V = \frac{v_o d^2}{72 A_x^{.25} A_y^{.75}} \quad . \qquad (B11.6)$$

Figure (B-4) illustrates the virtual distance concept.

11. Investigation of the Dose Level in the Vertical Direction

In order to examine the dose level as a function of the

distance above the point of release for an instantaneous release

case without decay, it is necessary to begin with Equation (B1.3).

If x and y are set equal to zero and it is assumed that the mean

current velocity in the z-direction is zero, then this equation

becomes

$$S_i(t,z) = \frac{\alpha\, M\, t^{-3/2}}{\sqrt{1+\beta t^2}} \quad \exp - \left[\frac{1 + (\frac{1}{12}\,\Omega_y^2\,\frac{A_y}{A_x} + \frac{1}{3}\,\Omega_z^2\,\frac{A_z}{A_x})t^2}{4A_z t(1+\beta t^2)}\, z^2 \right].$$

(B11.1)

Allowing for the reflection from the sea floor, the dose rate due to the mixed fission product release inventory will be

$$D(t,z) = \frac{2\left\{\displaystyle\sum_{n=1}^{7} \varepsilon_n M_n\right\}\alpha}{t^{3/2}\,\sqrt{1+\beta t^2}} \quad \exp - \left[\frac{1 + (\frac{1}{12}\,\Omega_y^2\,\frac{A_y}{A_x} + \frac{1}{3}\,\Omega_z^2\,\frac{A_z}{A_x})t^2}{4A_z t(1+\beta t^2)}\, z^2 \right].$$

(B11.2)
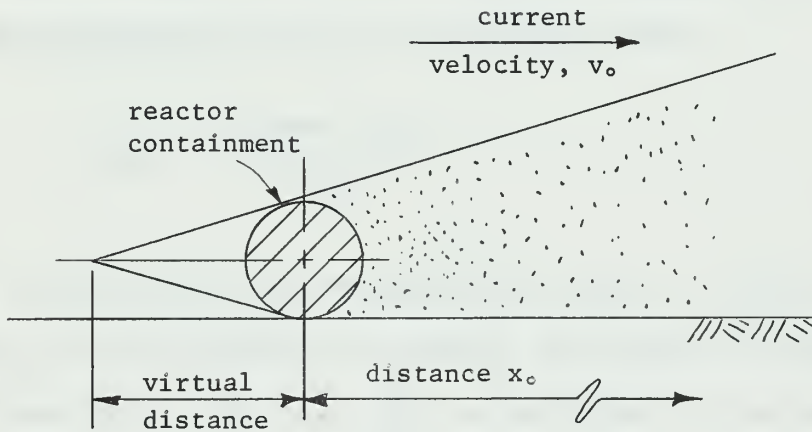
Figure B-4.   Virtual Distance Concept

APPENDIX C

DETERMINATION OF THE MAXIMUM PERMISSIBLE CONCENTRATION
OF A RADIOISOTOPE IN SEAWATER (MPCC)[14]

Case I.   Specific Activity Method

For those cases in which the limiting intake is determined by body burden, then

$$MPCC = \frac{S \, q \, I_{nw}}{I_{nb}} \times \frac{(\lambda + B)}{B} \tag{C1.1}$$

MPCC's for radioisotopes in Case I are given in Table C-1.

Case II.   Concentration Factor Method

For those cases in which the intake is limited by irradiation of the gastrointestinal tract by its contents, then

$$MPCC = \frac{S \, (MPC) \, I_{nw}}{I_{ns}} \, F \tag{C1.2}$$

where F is the ratio of the consumption of water, in liters per kilogram, to the consumption of seafood. The factor F is approximately equal to 10. The term $\frac{I_{ns}}{I_{nw}}$ is equivalent to the concentration factor of the seafood, f. Hence, Equation (C1.2) may be written

$$MPCC = \frac{S \, (MPC) \, F}{f} \tag{C1.3}$$

MPCC's for radioisotopes in Case II are given in Table C-2.

The natural chemical abundance of the carrier in seawater is an extremely important factor in calculating MPCC's. This factor enters into the calculations either directly (specific activity method) or indirectly through the concentration factor (concentration factor method). Table C-3 gives the average chemical abundances of the elements in seawater. Goldberg[12] points out that such a tabulation as this suffers from the fact that many of the values are from a single set of analyses of surface waters and as such are quite possibly uncharacteristic of the ocean environment as a whole.

Table C-1. Calculation of MPCC for Radioisotopes for Which Limiting Intake Is Determined by Body Burden – Specific Activity Method

Isotope	Element	Carrier	Critical Organ	Maximum Permissible Body Burden In Critical Organ q (μc)	Quantity of Carrier in Critical Organ I_{nb} (grams)	Decay Factor $\frac{\lambda+B}{B}$	Conc. of Carrier in Seawater I_{nw} (gr/kg)	Maximum Permissible Concentration In Seawater MPCC ($\mu c/kg$)
Br^{82}	Bromine	Br	Total Body	1.0×10^{1}	1.19×10^{-1}	6.3	6.5×10^{-2}	3.4×10^{-1}
Rb^{86}	Rubidium	Rb	Total Body	3.0×10^{1}	1.2×10^{0}	3.4	1.2×10^{-4}	1.0×10^{-3}
Rb^{87}	Rubidium	Rb	Total Body	2.0×10^{2}	1.2×10^{0}	1.0	1.2×10^{-4}	2.0×10^{-3}
Sr^{89}	Strontium	Sr	Bone	4.0×10^{0}	1.3×10^{-1}	356	8.0×10^{-3}	8.8×10^{0}
Sr^{90}	Strontium	Sr	Bone	2.0×10^{0}	1.3×10^{-1}	2.8	8.0×10^{-3}	3.4×10^{-2}
Zr^{93}	Zirconium	RE	Bone	8.0×10^{1}	5.0×10^{-2}	1.0	3.0×10^{-5}	4.8×10^{-3}
Nb^{93m}	Niobium	Nb	Bone	9.4×10^{1}	2.5×10^{-2}	1.3	1.0×10^{-8}	4.9×10^{-6}
Nb^{95}	Niobium	Nb	Total Body	4.0×10^{1}	5.0×10^{-2}	22.7	1.0×10^{-8}	1.8×10^{-4}
Mo^{99}	Molybdenum	Mo	Kidney	5.2×10^{-1}	1.2×10^{-4}	2.1	1.0×10^{-5}	8.9×10^{-3}
Sb^{125}	Antimony	Sb	Total Body	6.0×10^{1}	9.0×10^{-2}	1.0	5.0×10^{-7}	3.5×10^{-5}
Te^{125m}	Tellurium	Te	Testis	1.0×10^{-1}	1.2×10^{-2}	1.5	8.0×10^{-8}	1.0×10^{-7}
Te^{127m}	Tellurium	Te	Testis	3.5×10^{-2}	1.2×10^{-2}	1.3	8.0×10^{-8}	3.0×10^{-8}
Te^{129m}	Tellurium	Te	Testis	1.5×10^{-2}	1.2×10^{-2}	1.9	8.0×10^{-8}	2.0×10^{-8}

Table C-1 (continued)

			q	I_{nb}	$\frac{\lambda+B}{B}$	I_{nw}	MPCC
I^{129}	Iodine	Thyroid	6.0×10^{-1}	8.0×10^{-3}	1.0	6.0×10^{-5}	4.5×10^{-4}
I^{131}	Iodine	Thyroid	1.4×10^{-1}	8.0×10^{-3}	18.4	6.0×10^{-5}	2.0×10^{-3}
I^{132}	Iodine	Thyroid	6.0×10^{-2}	8.0×10^{-3}	1400	6.0×10^{-5}	6.3×10^{-2}
I^{133}	Iodine	Thyroid	6.0×10^{-2}	8.0×10^{-3}	160	6.0×10^{-5}	7.2×10^{-3}
I^{134}	Iodine	Thyroid	4.0×10^{-2}	8.0×10^{-3}	3800	6.0×10^{-5}	1.1×10^{-1}
I^{135}	Iodine	Thyroid	6.0×10^{-2}	8.0×10^{-3}	500	6.0×10^{-5}	2.3×10^{-2}
Cs^{135}	Cesium	Liver	1.8×10^{1}	1.0×10^{-5}	1.0	5.0×10^{-7}	9.0×10^{-2}
Cs^{136}	Cesium	Total Body	3.0×10^{1}	1.0×10^{-5}	6.4	5.0×10^{-7}	9.6×10^{-1}
Cs^{137}	Cesium	Total Body	3.0×10^{1}	1.0×10^{-5}	1.0	5.0×10^{-7}	1.5×10^{-1}
Nd^{144}	Neodymium	Bone	8.0×10^{-2}	5.0×10^{-2}	1.0	3.0×10^{-5}	4.8×10^{-6}
Sm^{147}	Samarium	Bone	8.0×10^{-2}	5.0×10^{-2}	1.0	3.0×10^{-5}	4.8×10^{-6}

Table C-2. Calculations of MPCC for Radioisotopes for Which Limiting
           Intake is Determined by Irradiation of the Gastrointestinal
           Tract — Concentration Factor Method

Isotope	Element	Critical Organ	Concentration Factor in Seafood	Maximum Permissible Conc. in Drinking Water	Maximum Permissible Conc. in Seawater
			f	MPC (μc/kg)	MPCC (μc/kg)
Ga^{72}	Gallium	GI(LLI)	8.0×10^2	4×10^{-1}	5.0×10^{-4}
As^{77}	Arsenic	GI(LLI)	3.3×10^3	8×10^{-1}	2.5×10^{-4}
Sr^{91}	Strontium	GI(LLI)	2.0×10^1	7×10^{-1}	3.5×10^{-2}
Sr^{92}	Strontium	GI(ULI)	2.0×10^1	7×10^{-1}	3.5×10^{-2}
Y^{90}	Yttrium	GI(LLI)	1.0×10^3	2×10^{-1}	2.0×10^{-4}
Y^{91}	Yttrium	GI(LLI)	1.0×10^3	3×10^{-1}	3.0×10^{-4}
Y^{91m}	Yttrium	GI(SI)	1.0×10^3	3×10^1	3.0×10^{-2}
Y^{92}	Yttrium	GI(ULI)	1.0×10^3	6×10^{-1}	6.0×10^{-4}
Y^{93}	Yttrium	GI(LLI)	1.0×10^3	3×10^{-1}	3.0×10^{-4}
Zr^{95}	Zirconium	GI(LLI)	1.0×10^3	6×10^{-1}	6.0×10^{-4}
Zr^{97}	Zirconium	GI(LLI)	1.0×10^3	2×10^{-1}	2.0×10^{-4}
Nb^{97}	Niobium	GI(ULI)	2.0×10^2	9×10^0	4.5×10^{-2}
Tc^{99}	Technetium	GI(LLI)	5.0×10^4	3×10^0	6.0×10^{-5}
Tc^{99m}	Technetium	GI(ULI)	5.0×10^4	6×10^1	1.2×10^{-3}
Ru^{103}	Ruthenium	GI(LLI)	5.0×10^4	8×10^{-1}	1.6×10^{-5}
Ru^{105}	Ruthenium	GI(ULI)	5.0×10^4	1×10^0	2.0×10^{-5}
Ru^{106}	Ruthenium	GI(LLI)	5.0×10^4	1×10^{-1}	2.0×10^{-6}
Rh^{105}	Rhodium	GI(LLI)	?	1×10^0	?
Pb^{109}	Lead	GI(LLI)	2.6×10^3	9×10^{-1}	3.5×10^{-4}
Ag^{110m}	Silver	GI(LLI)	2.2×10^4	3×10^{-1}	1.4×10^{-5}
Ag^{111}	Silver	GI(LLI)	2.2×10^4	4×10^{-1}	1.9×10^{-5}
Cd^{115}	Cadmium	GI(LLI)	2.0×10^4	3×10^{-1}	1.5×10^{-5}
In^{115}	Indium	GI(ULI)	4.0×10^5	9×10^{-1}	2.3×10^{-6}
In^{115m}	Indium	GI(ULI)	4.0×10^5	4×10^0	1.0×10^{-5}

Table C-2 (continued)

			f	MPC (μc/kg)	MPCC (μc/kg)
Sn^{125}	Tin	GI(LLI)	2.0×10^3	2×10^{-1}	1.0×10^{-4}
Te^{127}	Tellurium	GI(LLI)	1.0×10^2	3×10^0	3.0×10^{-2}
Te^{129}	Tellurium	GI(S)	1.0×10^2	8×10^0	8.0×10^{-2}
Te^{131m}	Tellurium	GI(LLI)	1.0×10^2	6×10^{-1}	6.0×10^{-3}
Te^{132}	Tellurium	GI(LLI)	1.0×10^2	3×10^{-1}	3.0×10^{-3}
Ba^{140}	Barium	GI(LLI)	5.0×10^2	3×10^{-1}	6.0×10^{-4}
La^{140}	Lanthanum	GI(LLI)	1.0×10^3	2×10^{-1}	2.0×10^{-4}
Ce^{141}	Cerium	GI(LLI)	1.0×10^3	9×10^{-1}	9.0×10^{-4}
Ce^{143}	Cerium	GI(LLI)	1.0×10^3	4×10^{-1}	4.0×10^{-4}
Ce^{144}	Cerium	GI(LLI)	1.0×10^3	1×10^{-1}	1.0×10^{-4}
Pr^{143}	Praseodymium	GI(LLI)	1.0×10^3	5×10^{-1}	5.0×10^{-4}
Nd^{147}	Neodymium	GI(LLI)	1.0×10^3	6×10^{-1}	6.0×10^{-4}
Nd^{149}	Neodymium	GI(LLI)	1.0×10^3	3×10^0	3.0×10^{-3}
Pm^{147}	Promethium	GI(LLI)	1.0×10^3	2×10^0	2.0×10^{-3}
Pm^{149}	Promethium	GI(LLI)	1.0×10^3	4×10^{-1}	4.0×10^{-4}
Sm^{151}	Samarium	GI(LLI)	1.0×10^3	4×10^0	4.0×10^{-3}
Sm^{153}	Samarium	GI(LLI)	1.0×10^3	8×10^{-1}	8.0×10^{-4}
Eu^{155}	Europium	GI(LLI)	1.0×10^3	2×10^0	2.0×10^{-3}
Gd^{159}	Gadolinium	GI(LLI)	1.0×10^3	8×10^{-1}	8.0×10^{-4}

Table C-3.   Chemical Abundances in Seawater[12]

Element	Abundance mg/1	Element	Abundance mg/1	Element	Abundance mg/1
H	1.1×10^5	Ge	7.0×10^{-5}	Eu	–
He	5.0×10^{-6}	As	3.0×10^{-3}	Gd	–
Li	1.7×10^{-1}	Se	4.0×10^{-3}	Tb	–
Be	6.0×10^{-7}	Br	6.5×10^1	Dy	–
B	4.6×10^0	Kr	3.0×10^{-4}	Ho	–
C	2.8×10^1	Rb	1.2×10^{-1}	Er	–
N	5.0×10^{-1}	Sr	8.0×10^0	Tm	–
O	8.6×10^5	Y	3.0×10^{-4}	Yb	–
F	1.3×10^0	Zr	–	Lu	–
Ne	1.0×10^{-4}	Nb	1.0×10^{-5}	Hf	–
Na	1.1×10^4	Mo	1.0×10^{-2}	Ta	–
Mg	1.4×10^3	Tc	–	W	1.0×10^{-4}
Al	1.0×10^{-2}	Ru	–	Re	–
Si	3.0×10^0	Rh	–	Os	–
P	7.0×10^{-2}	Pd	–	Ir	–
S	8.9×10^2	Ag	3.0×10^{-4}	Pt	–
Cl	1.9×10^4	Cd	1.1×10^{-4}	Au	4.0×10^{-6}
A	6.0×10^{-1}	In	2.0×10^{-2}	Hg	3.0×10^{-5}
K	3.8×10^2	Sn	3.0×10^{-3}	Tl	1.0×10^{-5}
Ca	4.0×10^2	Sb	5.0×10^{-4}	Pb	3.0×10^{-5}
Sc	4.0×10^{-5}	Te	–	Bi	–
Ti	1.0×10^{-3}	I	6.0×10^{-2}	Po	–
V	2.0×10^{-3}	Xe	1.0×10^{-4}	At	–
Cr	5.0×10^{-5}	Cs	5.0×10^{-4}	Rn	6.0×10^{-16}
Mn	2.0×10^{-3}	Ba	1.0×10^{-2}	Fr	–
Fe	1.0×10^{-2}	La	3.0×10^{-4}	Ra	1.0×10^{-10}
Co	5.0×10^{-4}	Ce	4.0×10^{-4}	Ac	–
Ni	2.0×10^{-3}	Pr	–	Th	5.0×10^{-5}
Cu	3.0×10^{-3}	Nd	–	Pa	2.0×10^{-9}
Zn	1.0×10^{-2}	Pm	–	U	3.0×10^{-3}
Ga	3.0×10^{-5}	Sm	–		

APPENDIX D

FISSION PRODUCT INVENTORY

The fission product inventory to which the release assumptions
of Chapter 4 are applied in order to obtain the fission product release
inventory is presented in Table D-1. Table D-1 includes all fission
product radioisotopes with a half life of over four minutes (6.67×10^{-2}
hours) which decay by the emission of gamma photons of over 0.1 Mev
energy. In addition, the inventory includes those fission products
which are not gamma emitters but for which maximum permissible body
burdens have been established.

The inventories are calculated, using ORNL 2127[27], on the basis
of an irradiation time of 3×10^{7} seconds (approximately 347 days);
time after shutdown equal to zero; and a neutron flux of 10^{14} neutrons
per square centimeter per second.

Solubility informaton was obtained from the Handbook of Chemistry
and Physics.[28]

Table D-1. Fission Product Inventory

Element	Isotope	Fission Product Inventory		Half Life	Solubility in
		By Element (curies/MW	By Isotope (curies/MW)	(hours)	Cold Water (mg/1)
Zinc		< 1			
	72		< 1	4.90×10^{1}	insol.
Gallium		1			insol.
	72		< 1	1.43×10^{1}	
	73		< 1	5.00×10^{0}	
Germanium		191			insol.
	75		7	1.37×10^{0}	
	77		32	1.20×10^{1}	
	78		152	1.43×10^{0}	
Arsenic		1,619			insol.
	77		77	3.88×10^{1}	
	78		172	1.52×10^{0}	
	79		300	1.50×10^{-1}	
	81		1,070	1.67×10^{-1}	
Selenium		1,752			insol.
	79		< 1	5.69×10^{8}	
	81		175	2.84×10^{-1}	
	81m		57	9.42×10^{-1}	
	83		1,510	4.17×10^{-1}	

Table D-1. (continued)

| Element | Isotope | Fission Product Inventory | | Half Life | Solubility in |
		By Element (curies/MW)	By Isotope (curies/MW)	(hours)	Cold Water (mg/l)
Bromine		13,520			6.50×10^1
	82		10	3.59×10^1	
	83		4,050	2.40×10^0	
	84		9,460	5.00×10^{-1}	
Krypton		72,169			$110 \ cm^3/\ell$
	83m		4,050	1.90×10^0	
	85		119	9.00×10^4	
	85m		12,500	4.36×10^0	
	87		23,300	1.30×10^0	
	88		32,200	2.77×10^0	
Rubidium		121,426			decomp.
	86		26	4.68×10^2	
	88		31,900	2.96×10^{-1}	
	89		39,200	2.50×10^{-1}	
	91		50,300	2.34×10^{-1}	
Strontium		195,830			decomp.
	89		37,200	1.30×10^3	
	90		1,230	2.45×10^5	
	91		50,300	9.70×10^0	
	92		53,000	2.70×10^0	
	93		54,100	1.17×10^{-1}	
Yttrium		291,740			sl. decomp.
	90		1,340	6.45×10^1	
	91		51,000	1.39×10^3	
	91m		20,200	8.50×10^{-1}	
	92		52,400	3.60×10^0	
	93		55,000	1.00×10^1	
	94		56,200	2.75×10^{-1}	
	95		55,600	1.75×10^{-1}	

Table D-1. (continued)

| Element | Isotope | Fission Product Inventory | | Half Life | Solubility in Cold Water |
		By Element (curies/MW)	By Isotope (curies/MW	(hours)	(mg/l)
Zirconium		106,300			insol.
	95		52,500	1.51×10^3	
	97		53,800	1.70×10^1	
Niobium		111,524			insol.
	93m		7,500	3.24×10^4	
	95		51,100	8.40×10^2	
	95m		519	9.00×10^1	
	96		5	2.34×10^1	
	97		52,400	1.20×10^0	
Molybdenum		128,700			insol.
	99		51,400	6.70×10^1	
	101		41,300	2.44×10^{-1}	
	102		36,000	2.00×10^{-1}	
Technetium		46,780			?
	99m		5,180	6.04×10^0	
	101		41,600	2.33×10^{-1}	
Ruthenium		35,340			insol.
	103		24,600	9.84×10^2	
	105		7,500	4.50×10^0	
	106		1,520	8.76×10^3	
	107		1,720	6.67×10^{-2}	
Rhodium		33,722			insol.
	103		23,900	9.00×10^{-1}	
	105		7,860	3.65×10^1	
	107		1,720	4.34×10^{-1}	
	109		242	1.00×10^0	
Lead		502			insol.
	109		255	1.36×10^1	
	111		156	3.67×10^{-1}	
	112		91	2.10×10^1	

Table D-1. (continued)

Element	Isotope	Fission Product Inventory		Half Life	Solubility in
		By Element (curies/MW)	By Isotope (curies/MW)	(hours)	Cold Water (mg/1)
Silver		460			insol.
	110m		30	6.48×10^3	
	111		157	1.82×10^2	
	112		95	3.20×10^0	
	113		87	5.30×10^0	
	115		91	3.33×10^{-1}	
Cadmium		350			insol.
	115		87	5.30×10^1	
	115		6	1.03×10^3	
	117		86	8.35×10^{-1}	
	117m		84	2.90×10^0	
	118		87	5.00×10^{-1}	
Indium		366			insol.
	115m		90	4.50×10^0	
	117		19	1.10×10^0	
	117m		85	1.90×10^0	
	118		89	7.50×10^{-2}	
	119		83	2.92×10^{-1}	
Tin		3,282			insol.
	117m		< 1	3.36×10^2	
	119m		< 1	6.60×10^3	
	121		118	2.75×10^1	
	123		9	3.14×10^3	
	123		118	6.59×10^{-1}	
	125		144	2.26×10^2	
	126		862	8.35×10^{-1}	
	127		2,030	1.50×10^0	
Antimony		55,597			insol.
	125		41	2.37×10^4	
	126		856	9.00×10^0	
	127		2,140	9.30×10^1	
	128		4,300	1.10×10^0	
	129		8,860	4.60×10^0	
	130		17,200	2.00×10^{-1}	
	131		22,200	3.50×10^{-1}	

Table D-1.   (continued)

Element	Isotope	Fission Product Inventory		Half Life	Solubility in Cold Water
		By Element (curies/MW)	By Isotope (curies/MW)	(hours)	(mg/1)
Tellurium		187,143			insol.
	125m		5	1.39×10^3	
	127		2,030	9.30×10^0	
	127m		278	2.16×10^3	
	129		8,350	1.20×10^0	
	129m		2,890	7.92×10^2	
	131		24,400	4.14×10^{-1}	
	131m		3,890	3.00×10^1	
	132		37,300	7.70×10^1	
	133m		51,800	1.05×10^0	
	134		56,200	7.33×10^{-1}	
Iodine		233,800			2.92×10^2
	131		23,600	1.93×10^2	
	132		38,100	2.40×10^0	
	133		55,100	2.08×10^1	
	134		65,400	8.76×10^{-1}	
	135		51,600	6.68×10^0	
Xenon		125,368			241 cm^3/ℓ
	131m		258	2.88×10^2	
	133		1,350	1.26×10^3	
	133m		56,200	5.52×10^1	
	135		3,760	9.20×10^0	
	135m		15,400	2.60×10^{-1}	
	138		48,400	2.83×10^{-1}	
Cesium		93,932			decomp.
	136		212	3.12×10^2	
	137		1,020	2.33×10^5	
	138		43,500	5.35×10^{-1}	
	139		49,200	1.58×10^{-1}	
Barium		203,000			decomp.
	139		52,400	1.42×10^0	
	140		54,000	3.07×10^2	
	141		49,500	3.00×10^{-1}	
	142		47,100	1.00×10^{-1}	

Table D-1.   (continued)

| Element | Isotope | Fission Product Inventory | | Half Life | Solubility in |
		By Element (curies/MW)	By Isotope (curies/MW)	(hours)	Cold Water (mg/1)
Lanthanum					decomp.
	140		54,000	4.02×10^{1}	
	141		51,000	3.70×10^{0}	
	142		51,000	1.23×10^{0}	
	143		54,100	3.17×10^{-1}	
Cerium		210,100			insol.
	141		51,800	7.68×10^{2}	
	143		53,500	3.30×10^{1}	
	144		29,200	6.96×10^{3}	
	146		27,100	2.32×10^{-1}	
Praseodymium		146,000			decomp.
	143		52,100	3.29×10^{2}	
	144		28,700	2.92×10^{-1}	
	145		36,200	6.00×10^{0}	
	146		29,000	4.06×10^{-1}	
Neodymium		15,861			decomp.
	147		221	2.71×10^{2}	
	149		11,500	2.00×10^{0}	
	151		4,140	2.50×10^{-1}	
Promethium		19,970			?
	147		4,210	2.28×10^{4}	
	149		11,600	5.40×10^{1}	
	151		4,160	2.75×10^{1}	
Samarium		2,534			insol.
	151		< 1	8.15×10^{5}	
	153		2,150	4.70×10^{1}	
	155		271	3.92×10^{-1}	
	156		112	1.00×10^{1}	

Table D-1. (continued)

| Element | Isotope | Fission Product Inventory | | Half Life | Solubility in |
		By Element (curies/MW)	By Isotope (curies/MW)	(hours)	Cold Water (mg/1)
Europium		455			insol.
	155		3	1.56×10^4	
	156		372	3.70×10^2	
	157		63	1.54×10^1	
	158		17	1.00×10^0	
Gadolinium		10			insol.
	159		10	1.80×10^1	
Terbium		< 1			insol.
	161		< 1	1.68×10^2	

APPENDIX E

"SEADIF" COMPUTER PROGRAM

Two separate and complete computer programs have been written. SEADIF I (Table E-1) is a FORTRAN IV computer program for the uncontained reactor system whereas SEADIF II (Table E-2) treats the contained system. With the information shown in Table E-3, provided in the format given by Figure E-1, the following results may be obtained:

   a. Dose rate as a function of the distance from the reactor at four hours after release

   b. The integrated dose received in the first four hours after release as a function of distance from the reactor

   c. The integrated dose received for an infinite period of time after release as a function of distance from the reactor

   d. The exclusion radius

   e. The low population radius

   f. The time (or in the case of SEADIF II - the distance) required for the concentration of a specific fission product to reach MPCC.

SEADIF I evaluates Equations (B6.4), (B6.5), (B6.6), and (B6.7) in determining the dose rate and total integrated dose received. In the low population dose, an upper limit is set by successively evaluating Equation (B6.5) until the numerical value of this function is less than 1/1000 the value of the function at its maximum.

SEADIF II evaluates Equations (B8.1) through (B8.7) by numerical integration techniques employing the Gaussian numerical integration library function DGNTGR.

Both programs require that current velocity and distance from point of release be provided as input data. The programs provide complete exclusion radius, low population radius, and dose rate results for each current velocity (up to 16 maximum on any one run) and safety radius results for the maximum current velocity. A zero velocity input may be used although such an input will require more computer time, especially for the continuous release case.

It is important that the distance used be ordered smallest to largest and the interval between distance points be kept reasonable. Reasonable distance intervals (on the order of 500 meters) result in computer time savings. Under no conditions should the distance intervals exceed 5,000 meters. Up to 40 distances from point of release may be provided as input data. The minimum distance that may be used is five meters. However, because of fundamental release and decay assumptions, results for distances of less than 20 meters must be used judiciously. At these small distances, round off error from the numerical integration techniques may become large. Excessive roundoff error will be noted by a numeral 1 appearing under the column headed ERROR in the program output.

Both programs have a virtual distance option. Providing the containment diameter on the appropriate card in Table E-3 will correct all distances by an amount equal to the virtual distance, V, as computed from Equation (10.6). A zero containment diameter or a blank

card will call for a zero correction. Cards for up to 200 isotopes may be provided as input for the fission product release inventory calculations. For the results presented in Chapter 6, the data shown in Appendices C and D was used. Omission of any isotope results in a smaller release inventory and corresponding reductions in the dose rates and distance factors. It is important to include all fission products with a half life of over four minutes and their decay information by energy group whether or not an MPCC has been established. Omission of the MPCC from a data card results in the omission of the peak concentration (safety radius) calculations for that isotope and does not effect the release inventory.

If it is desired to change the release percentages for the soluble and insoluble isotopes, or for that matter, any single isotope, this may be done in the last data field of the isotope information card.

Representative computer time for five velocity cases and 15 distances is about 30 seconds for SEADIF I and about 100 seconds for SEADIF II. For SEADIF II, the smaller current velocities require more computer time.

Table E-1. FORTRAN IV Computer Program for an
Uncontained Reactor System

```
C       *****SEADIF*****
C       INSTANTANEOUS RELEASE CASE
C       WITH DECAY
C
        IMPLICIT REAL*8(A-H,O-Z)
        EXTERNAL FCT,WOD
        COMMON ALPHA,BETA,AX,NX/ISOT/IDENT(200),AMT(200),PCC(200),
       1DIST(200),TIME(200),PER(200),HALF(200)/FUN/VEL,XX
        DIMENSION VO(16),XO(40),GAM(200,7),A(200,7),ANS(10),POP(40),
       1SUM(7),EN(7),TEMP(7),AUX(1000),RINT(40),DOSER(40),VDIS(16)
        PRINT 10
10      FORMAT ('1*****SEADIF*****   INSTANTANEOUS RELEASE CASE')
        READ 11,POWER
11      FORMAT (F10.4)
        PRINT 12,POWER
12      FORMAT ('0POWER=',F10.4,'  MW')
C
C       READ IN CURRENT INFO AND COMPUTE ALPHA AND BETA
C
        READ 13,AX,AY,AZ,OMEGAY,OMEGAZ
13      FORMAT (2F10.3,3D10.3)
        ALPHA=1.0/8.0/3.1415927**1.5/DSQRT(AX*AY*AZ)
        BETA=(OMEGAY**2*AY/AX+OMEGAZ**2*AZ/AX)/12.0
        PRINT 14,AX,AY,AZ,OMEGAY,OMEGAZ,ALPHA,BETA
14      FORMAT(' AX=',F10.5'   METERS SQUARED PER SEC'/
       1'AY=',F10.5,'   METERS SQUARED PER SEC'/
       2' AZ=',F10.5,'   METERS SQUARED PER SEC'/
       3' OMEGA Y=',D10.3,'   PER SEC'/
       4' OMEGA z=',D10.3,'   PER SEC'/
       5' ALPHA =',D10.3,'   SEC*3/2 PER METER*3'/
       6' BETA =',D10.3,'   PER SEC SQUARED')
        READ 15,NV,NX
15      FORMAT (2I3)
        READ 16,(VO(I),I=1,NV)
        READ 17,(XO(I),I=1,NX)
16      FORMAT (8F10.4)
17      FORMAT (8F10.2)
C
C       READ IN EQUIVALENT CONTAINMENT DIAMETER (METERS) AND COMPUTE THE
C       VIRTUAL DISTANCES FOR THE GIVEN VELOCITIES.
C
        READ 18,DIAM
18      FORMAT (F10.2)
        PRINT 19,DIAM
19      FORMAT (' CONTAINMENT DIAMETER =',F10.2,'  METERS')
        VIRT=DIAM**2/72.0/AX**0.75/AY**0.25
        DO 20 I-1,NV
20      VDIS(I)=I*VIRT
```

Table E-1. (continued)

```
C
C       READ IN ISOTOPE INFO AND COMPUTE SOURCE TERM
C
        READ 21,NI
   21 FORMAT (13)
        READ 22,((IDENT(I),AMT(I),PCC(I),HALF(I),(GAM(I,J),J=1,7),
       IPER(I)),I=I,NI)
   22 FORMAT (I5,5X,3DIO.3,7F5.1,F5.3)
        DO 23 I=1,NI
        DO 23 J=1,7
        A(I,J)=AMT(I)*GAM(I,J)*PER(I)*0.01*POWER
   23 CONTINUE
        DO 24 J=1,7
        SUM(J)=0.0
        DO 24 I=1,NI
        SUM(J)=SUM(J)+A(I,J)
   24 CONTINUE
        EN(1)=4.30D-15
        EN(2)=1.46D-14
        EN(3)=2.04D-14
        EN(4)=3.17D-14
        EN(5)=2.05D-14
        EN(6)=4.17D-14
        EN(7)=5.26D-14
        XEM=0.0
        DO 25 J=1,7
        TEMP(J)=EN(J)*SUM(J)
        XEM=XEM+TEMP(J)
   25 CONTINUE
        XEM=XEM*3.7D+10
        PRINT 26,XEM
   26 FORMAT (' XEM='D10.3,'  RM*3/SEC')
C
C       DETERMINE DOSE RATE AT 4 HRS AND TOTAL DOSE RECEIVED IN
C       FIRST 4 HRS.
C
        PRINT 28
   28 FORMAT ('1RADIATION DOSAGE INFORMATION'/10X,'DOSE RATE IN'
       1' R/HR AT TIME=4HRS AFTER RELEASE'/10X,'GAMMA DOSE '
       2'RECEIVED UP TO 4 HRS AFTER RELEASE'/10X,'EXCLUSION RADIUS'
       3' BASED ON DOSE NOT TO EXCEED 25R'//'0  DIST(M)       VEL(M)'
       4'SEC)    DOSE RATE(R/HR)     DOSE(R)     LOW POP DOSE    '
       5'ERROR    LIMIT    INTERVAL   VIRT DIST(M)')
        EPS=0.01
        NDIM=12
        DO 64 I=1,NV
        VEL=VO(I)
        DO 41 J=1,NX
        TRY1=0.0
        TRY2=0.0
        XX=XO(J)+VDIS(I)
```

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Table E-1. (continued)

```
      DRT=1.44D+4
      DOSER(J)=XEM*ALPHA*FCT(DRT)*2.86632D+7
      CALL LIMIT(XX,VEL,XL,XU,IERR)
      IF (XU.GT.1.44D+04)XU=1.44D+04
      IF (VEL.LT.0.02) GO TO 29
      IF (XU.EQ.1.44D+04)XL=L=1.00D+03
      IF (XL.EQ.1.00D+03)IERR=5
   29 IF (XL.LT.1000.0) GO TO 37
      IF (XL.GE.1.44D+04)XL=1.00D+03
      CALL DQATR(XL,XU,EPS,NDIM,FCT,S,IER,AUX)
      RINT(J)=XEM*ALPHA*S*7.962D+3
C
C     DETERMINE LOW POPULATION DOSE
C
   31 SAVE=0.0
      K=1
   32 XL=XU
      XU=2.0*XU
      IF (XL.LT.1000.0) GO TO 39
      CALL DQATR(XL,XU,EPS,NDIM,FCT,ANS(K),IR,AUX)
      PEXTR=XEM*ALPHA*ANS(K)*7.962D+3
   33 SAVE=SAVE+PEXTR
      IF (RINT(J).EQ.0.0) GO TO 34
      IF (PEXTR/RINT(J).LE.0.01) GO TO 35
   34 IF (K.EQ.10) GO TO 35
      K=K+1
      GO TO 32
   35 POP(J)=RINT(J)+SAVE
      PRINT 36,XO(J),VEL,DOSER(J),RINT(J),POP(J),IER,IERR,K,VDIS(I)
   36 FORMAT (' ',F10.3,5X,F10.4,5X,3(D11.4,5X),2(I2,8X),I2,5X,F10.5)
      GO TO 41
   37 XI=1000.0
      TRY2=0.0
      IERR=6
      CALL LOWER(XX,VEL,XLW,XUW,IEW)
      CALL DQATR(XLW,XOW,EPS,NDIM,WOD,SADD,IER,AUX)
      TRY1=XFM*ALPHA*SADD*2.0
      IF (XUW.LT.999.9) GO TO 38
      IF (XU.LE.1000.0) GO TO 38
      CALL DQATR(XI,XU,EPS,NDIM,FCT,S,IER2,AUX)
      TRY2=XEM*ALPHA*S*7.962D+3
   38 RINT(J)=TRY1+TRY2
      IER=IER+IER2
      GO TO 31
   39 XI=1000.0
      IF (XU.LT.1000.0)XI=XU
      IERR=IERR+10
      PALSO=0.0
      CALL DQATR(XL,XI,EPS,NDIM,WOD,ANS(K),IR,AUX)
      PADD=XEM*ALPHA*ANS(K)*2.0
      IF (XU.LE.1000.0) GO TO 40
```

Table E-1.   (continued)

```
      CALL DQATR(XI,XU,EPS,NDIM,FCT,ADD,IR,AUX)
      PALSO=XEM*ALPHA*ADD*7.962D+3
   40 PEXTR=PADD+PALSO
      GO TO 33
   41 CONTINUE
C
C     DETERMINE EXCLUSION RADIUS BY EVALUATING INTEGRAL AT IOM
C     INTERVALS UNTIL VALUE OF INTEGRAL IS LESS THAN 25R.
C
      IF (RINT(1)-25.0)  42,42,44
   42 PRINT 43,VO(1),XO(1)
   43 FORMAT (' FOR VELOCITY OF ',F10.4,'  M/SEC, THE EXCLUSION'
     1' RADIUS IS LESS THAN',F10.3,'  METERS')
      GO TO 56
   44 DO 54 K=2,NX
      IF (RINT(K)-25.0)  45,54,54
   45 XX=XO(K-1)+10.0+VDIS(1)
      DO 52 L=1,500
      CALL LIMIT(XX,VEL,XL,XU,IERR)
      IF (XU.GT.1.44D+04)XU=1.44D+04
      IF (VEL.LT.0.02) GO TO 46
      IF (XU.EQ.1.44D+04)XL=1.00D+03
   46 IF (XL.LT.1000.0) GO TO 50
      CALL DQATR(XL,XU,EPS,NDIM,FCT,S,IER,AUX)
      XCLU=XEM*ALPHA*S*7.962D+3
   47 IF (XCLU-25.0)  48,49,49
   48 XXX=XX-VDIS(I)
      PRINT 43,VO(I),XXX
      GO TO 56
   49 XX=XX+10.0
      GO TO 52
   50 XI=1000.0
      TRY2=0.0
      CALL LOWER(XX,VEL,XLW,XUW,IEW)
      CALL DQATR(XLW,XUW,EPS,NDIM,WOD,S,IER,AUX)
      TRY1=XEM*ALPHA*S*2.0
      IF (XUW.LT.999.9) GO TO 51
      IF (XU.LE.1000.0) GO TO 51
      CALL DQATR(XI,XU,EPS,NDIM,FCT,SADD,IER2,AUX)
      TRY2=XEM*ALPHA*SADD*7.962D+3
   51 XCLU=TRY1+TRY2
      GO TO 47
   52 CONTINUE
      PRINT 53,VO(I)
   53 FORMAT ('OFOR VELOCITY OF ',F10.4,'  M/SEC, AN ERROR EXISTS'
     1'REGARDING EXCLUSION RADIUS')
   54 CONTINUE
      PRINT 55,VO(I),XO(NX)
   55 FORMAT ('OFOR VELOCITY OF ',F10.4,'  M/SEC, THE EXCLUSION '
     1'RADIUS IS GREATER THAN',F10.3,'  METERS')
```

Table E-1   (continued)

```
C
C       FIND LOW POPULATION RADIUS(APPROXIMATE METHOD)
C
   56 IF (POP(1)-25.0)  57,57,59
   57 PRINT 58,XO(1)
   58 FORMAT (' ',35X,'THE LOW POPULATION RADIUS IS LESS THAN',F10.3,'
     1METERS'/)
      GO TO 64
   59 DO 60 N=2,NX
      IF (POP(N).LT.25.0) GO TO 62
   60 CONTINUE
      PRINT 61,XO(NX)
   61 FORMAT (' ',35X,'THE LOW POPULATION RADIUS IS GREATER THAN'
     1,F10.3.'  METERS'/)
      GO TO 64
   62 XCRE=(POP(N-1)-POP(N)/(XO(N)-XO(N-1))
      PLUS=(POP(N-1)-25.0)/XCRE
      RAD=XO(N-1)+PLUS
      PRINT 63,RAD
   63 FORMAT (' ',35X,'THE LOW POPULATION RADIUS IS APPROXIMATELY'
     1,F10.3,'  METERS'/)
   64 CONTINUE
C
C       PEAK CONCENTRATION LEVELS
C
      PRINT 66
   66 FORMAT ('1CRITICAL ISOTOPE INFORMATION'//'  ID'.8X,'CURIES/MW'
     1,5X,'MPCC(UC/KG      TIME(HRS)       DISTANCE(M)      HALF'
     2'LIFE(HRS)')
      VV=VO(NV)
      CALL PEAK(VV,NI,ALPHA,BETA,POWER)
      STOP
      END


      SUBROUTINE PEAK(VV,NI,ALPHA,BETA,POWER)
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON /ISOT/IDENT(200),AMT(200),PCC(200),DIST(200),TIME(200),
     1PER(200),HALF(200)
      BETAH=BETA*12.960+6
      DO 113 I=1,NI
      IF (PCC(I).LE.0.0)TIME(I)=0.0
      IF (PCC(I).LE.0.0) GO TO 113
      COF=(AMT(I)*ALPHA*POWER*PER(I)/PCC(1)**2*8.573388D-5
      XLAM=0.693/HALF(I)
      KOUNT=0
      T=1000.0
```

Table E-1. (continued)

```
100 IF (BETAH*T**5+T**3.GE.COF*DEXP(-2.0*XLAM*T)) GO TO 101
    IF (KOUNT+1.GE.100) GO TO 109
    T=T+1000.0
    GO TO 100
101 T=T-900.0
    KOUNT=0
102 IF (BETAH*T**5+T**3.GE.COF*DEXP(-2.0*XLAM*T)) GO TO 103
    IF (KOUNT+1.GE.10) GO TO 109
    T=T+100.0
    GO TO 102
103 T=T-90.0
    KOUNT=0
104 IF (BETAH*T**5+T**3.GE.COF*DEXP(-2.0*XLAM*T)) GO TO 105
    IF (KOUNT+1.GE.10) GO TO 109
    T=T+10.0
    GO TO 104
105 T=T-9.0
    KOUNT=0
106 IF (BETAH*T**5+T**3.GE.COF*DEXP(-2.0*XLAM*T)) GO TO 107
    IF (KOUNT+1.GE10) GO TO 109
    T=T+1.0
    GO TO 106
107 IF (T.GT.100.0) GO TO 111
    T=T-0.9
    KOUNT=0
108 IF (BETAH*T**5+T**3.GE.COF*DEXP(-2.0*XLAM*T)) GO TO 111
    IF (KOUNT+1.GE.10) GO TO 109
    T=T+0.1
    GO TO 108
109 PRINT 110,IDENT(I)
110 FORMAT (' ',I5,7X,'**ERROR MESSAGE-T GREATER THAN 1.0D+05 '
   1'HRS**')
    TIME(1)=0.0
    GO TO 113
111 TIME(I)=T
    DIST(I)=TIME(I)*VV*3.6D+3
    PRINT 112,IDENT(I),AMT(I),PCC(I),TIME(I),DIST(I),HALF(I)
112 FORMAT (' ',I5,5(5X,D10.3))
113 CONTINUE
    CRIT=TIME(1)
    IC=IDENT(1)
    DO 114 I=2,NI
    IF (TIME(I).GT.CRIT)CRIT=TIME(I)
    IF (CRIT.EQ.TIME(I))C=IDENT(I)
114 CONTINUE
    PRINT 115,IC,VV
115 FORMAT ('OTHE CRITICAL ISOTOPE IS ',I5,'. DISTANCES FOR '
   1'VELOCITY =',F10.4,' M/SEC')
    RETURN
    END
```

Table E-1. (continued)

```
        SUBROUTINE LIMIT(X,V,XL,XU,IERR)
C       LIMIT ERROR MESSAGE HAS THE FOLLOWING MEANINGS:
C       -0- UPPER AND LOWER LIMIT LESS THAN 4 HRS. NO ERROR
C       -1- UNABLE TO ACHIEVE DESIRED ACCURACY ON UPPER LIMIT.
C       -2- UNABLE TO ACHIEVE DESIRED ACCURACY ON LOWER LIMIT
C       -3- UNABLE TO ACHIEVE DESIRED ACCURACY ON EITHER UPPER
C           OR LOWER LIMITS.
C       -4- UPPER LIMIT SET EQUAL TO 4 HRS
C       -5- UPPER LIMIT SET EQUAL TO 4 HRS, LOWER LIMIT SET EQUAL
C           TO 1000 SECONDS.
        IMPLICIT REAL*8(A-H,O-Z)
        IF (V.EQ.0.0) GO TO 206
        IF (V.LT.0.01) GO TO 205
        IERR=0
        I=0
        TSET=X/V
        T=TSET
        TI=0.5*TSET
        IF (V.GT.0.149)TI=0.25*TSET
        TMAX=FCT(T)
    200 T=T+TI
        I=I+T
        IF (I.EQ.20) GO TO 204
        IF (FCT(T)/TMAX.GE.0.001) GO TO 200
        XU=T
    201 I=0
        TL=TSET
        IF (V.GT.0.149) GO TO 203
    202 TL=TL/2.0
        I=I+1
        IF (I.EQ.20) GO TO 207
        IF (FCT(TL)/TMAX.GE.0.001) GO TO 202
        XL=TL
        GO TO 208
    203 TL=0.75*TL
        I=I+1
        IF (I.EQ.20) GO TO 207
        IF (FCT(TL)/TMAX.GE.0.001) GO TO 203
        XL=TL
        GO TO 208
    204 XO=11.0*TSET
        IERR=1
        GO TO 201
    205 XU=1.44D+4
        XL=X
        IF (XL.GT.XU)XL=XU
        IERR=4
        GO TO 208
    206 XU=X*1.0D+6
        XL=X
        GO TO 208
    207 XL=1.0/2.0**20*TSET
```

Table E-1. (continued)

```
    IERR=IERR+2
208 RETURN
    END


    SUBROUTINE LOWER(X,V,XL,XU,IERR)
    IMPLICIT REAL*8(A-H,O-Z)
    IF (V.LT.0.01) GO TO 305
    IERR=0
    I=0
    TSET=X/V
    T=TSET
    TI=0.5*TSET
    IF (V.GT.0.149)TI=0.25*TSET
    TMAX=WOD(TSET)
300 T=T+TI
    I=I+1
    IF (I.EQ.20) GO TO 304
    IF (WOD(T)/TMAX.GE.0.001) GO TO 300
    XU=T
301 I=0
    TL=TSET
    IF (V.GT.0.149) GO TO 303
302 TL=TL/2.0
    I=I+1
    IF (I.EQ.20) GO TO 306
    IF (WOD(TL)/TMAX.GE.0.001) GO TO 302
    XL=TL
    GO TO 307
303 TL=0.75*TL
    I=I+1
    IF (I.EQ.20) GO TO 306
    IF (WOD(TL)/TMAX.GE.0.001) GO TO 303
    XL=TL
    GO TO 307
304 XU=11.0*TSET
    GO TO 301
305 XU-1000.0
    XL=X
    GO TO 308
306 XL=1.0/2.0**20*TSET
    IERR=IERR+20
307 IF (XU.GT.1000.0)XU=1000.0
    IF (XL.GT.1000.0)XL=1000.0
308 RETURN
    END
```

Table E-1. (continued)

```
FUNCTION FCT(T)
IMPLICIT REAL*8(A-H,O-Z)
COMMON ALPHA,BETA,AX,NX/FUN/VEL,XX
FCT=1.0/T**2.7/DSQRT(1.0+BETA*T**2)*DEXP(-(XX-VEL*T)**2/
1(4.0*AX*T*(1.0+BETA*T**2)))
RETURN
END


FUNCTION WOD(T)
IMPLICIT REAL*8(A-H,O-Z)
COMMON ALPHA,BETA,AX,NX/FUN/VEL,XX
WOD=1.0/T**1.5/DSQRT(1.0+BETA*T**2)*DEXP(-(XX-VEL*T)**2/
1(4.0*AX*T*(1.0+BETA*T**2)))
RETURN
END


/*
```

Table E-2. FORTRAN IV Computer Program for a
Contained Reactor System

```
C      *****SEADIF*****
C      CONTINUOUS RELEASE CASE
C      WITH DECAY
C
       IMPLICIT REAL*8(A-H,O-Z)
       EXTERNAL FCT
       COMMON ALPHA,BETA,AX,NX/ISOT/IDENT(200),AMT(200),PCC(200),
      1DIST(200),TIME(200)/FUN/VEL,XX/MISC/POWER,GAM(200,7),PER(200)
      1RTOT(40),CONC(40),VDIS(16)
C
C      PRINT HEADING,READ AND PRINT POWER LEVEL
C
       PRINT 10
   10 FORMAT ('1*****SEADIF***** CONTINUOUS RELEASE CASE')
       READ 11,POWER
   11 FORMAT (F10.4)
       PRINT 12,POWER
   12 FORMAT ('OPOWER=',F10.4,' MW')
C
C      READ IN CURRENT INFO AND COMPUTE ALPHA AND BETA
C
       READ 13,AX,AY,AZ,OMEGAY,OMEGAZ
   13 FORMAT (2F10.3,3D10.3)
       ALPHA=1.0/8.0/3.1415927**1.5/DSQRT(AX*AY*AZ)
       BETA=(OMEGAY**2*AY/AX+OMEGAZ**2*AZ/AX)12.0
       PRINT 15,AX,AY,AZ,OMEGAY,OMEGAZ,ALPHA,BETA
   15 FORMAT(' AX=',F10.3,'  METERS SQUARED PER SEC'/
      1' AY=',F10.5,'  METERS SQUARED PER SEC'/
      2' AZ=',F10.5,'  METERS SQUARED PER SEC'/
      3' OMEGA Y=',D10.3,'  PER SEC'/
      4' OMEGA Z=',D10.3,'  PER SEC'/
      5' ALPHA =',D10.3,'  SEC*3/2 PER METER*3'/
      6' BETA =',D10.3,'  PER SEC SQUARED')
       READ 16,NV,NX
   16 FORMAT (213)
       READ 17,(VO(I),I=1,NV)
       READ 18,(XO(I),I=1,NX)
   17 FORMAT (8F10.6)
   18 FORMAT (8F10.2)
       READ 19,RATE
   19 FORMAT (D10.3)
       PRINT 20,RATE
   20 FORMAT (' LEAKAGE RATE TO ENVIRONMENT=',D10.3,'  PER SEC')
```

Table E-2   (continued)

```
C
C        READ IN EQUIVALENT CONTAINMENT DIAMETER (METERS) AND COMPUTE THE
C        VIRTUAL DISTANCES FOR THE GIVEN VELOCITIES
C
         READ 21,DIAM
      21 FORMAT (F10.2)
         PRINT 22,DIAM
      22 FORMAT (' CONTAINMENT DIAMETER =',F10.2,'  METERS')
         VIRT=DIAM**2/72.0/AX**0.75/AY**0.25
         DO 23 I=1,NV
      23 VDIS(I)=VO(I)*VIRT
C
C        READ IN ISOTOPE INFO AND COMPUTE SOURCE TERM
C
         READ 24,NI
      24 FORMAT (I3)
         READ 25,((IDENT(I),AMT(I),PCC(I),HALF(I),(GAM(I,J),J=1,7,
        1PER(I)),I=1,NI)
      25 FORMAT (I5,5X,3D10.3,7F5.1,F5.3)
         CALL SOURCE(NI,XEM)
         PRINT 26,XEM
      26 FORMAT (' XEM='D10.3,'  RM*3/SEC')
C
C        COMPUTE DOSE RATE (STEADY STATE)
C
         PRINT 28
      28 FORMAT ('1RADIATION DOSAGE FOR STEADY STATE CONDITIONS'//
        1'    DIST(M)     VEL(M/SEC)    DOSE RATE(R/HR)    4HR DOSE(R)'
        2'   INFINITE DOSE  LIMIT    VIRT DIST(M)'/)
         NINT=500
         DAX=DSQRT(AX)
         DO 47 I=1,NV
         VEL=VO(I)
         IF (VEL.EQ.0.0)NINT=1200
         DO 32 J=1,NX
         XX=XO(J)+VDIS(I)
         IF (VEL.GE.0.1) GO TO 31
         CALL LIMIT(XX,VEL,XL,XU,IERR)
         S=DGNTGR(XL,XU,NINT,FCT)
      29 TERM(I,J)=2.0*S
         RHR(J)=XEM*RATE*ALPHA*146.52*TERM(I,J)
         RTOT(J)=XEM*RATE*ALPHA*3.066D+3*TERM(I,J)
         RPOP(J)=XEM*RATE*ALPHA*6.00D+3*TERM(I,J)
         PRINT 30,XO(J),VEL,RHR(J),RTOT(J),RPOP(J),IERR,VDIS(I)
      30 FORMAT (' ',F10.2,3X,F10.6,3(5X,D10.3),5X,I2,6X,F10.5)
         GO TO 32
      31 S=3.5449*DAX/XX
         IERR=0
         GO TO 29
      32 CONTINUE
```

Table E-2.   (continued)

```
C
C        DETERMINE EXCLUSION RADIUS
C
         IF (RTOT(1)-25.0) 34,34,36
      34 PRINT 35,VO(I),XO(1)
      35 FORMAT (' FOR VELOCITY OF ',F10.6,'  M/SEC, THE EXCLUSION'
        1' RADIUS IS LESS THAN',F10.3,'  METERS')
         GO TO 40
      36 DO 38 K=2,NX
         IF (RTOT(K)-25.0)  37,38,38
      37 XCRE=(RTOT(K-1)-RTOT(K))/(XO(K)-XO(K-1))
         PLUS=(RTOT(K-1)-25.0)/XCRE
         XCLU=XO(K-1)+PLUS
         PRINT 35,VO(I),XCLU
         GO TO 40
      38 CONTINUE
         PRINT 39,VO(I),XO(NX)
      39 FORMAT ('OFOR VELOCITY OF ',F10.6,'  M/SEC, THE EXCLUSION'
        1' RADIUS IS GREATER THAN',F10.3,'  METERS')
C
C        FIND LOW POPULATION RADIUS
C
      40 IF (RPOP(1).LT.25.0) GO TO 45
         DO 41 N=2,NX
         IF (RPOP(N).LT.25.0) GO TO 43
      41 CONTINUE
         PRINT 42,XO(NX)
      42 FORMAT(' ',35X,'THE LOW POPULATION RADIUS IS GREATER THAN',
        1F10.3,'  METERS'/)
         GO TO 47
      43 XCRE=(RPOP(N-1)-RPOP(N))/(XO(N)-XO(N-1))
         PLUS=(RPOP(N-1)-25.0)/XCRE
         RAD=XO(N-1)+PLUS
         PRINT 44,RAD
      44 FORMAT(' ',35X,'THE LOW POPULATION RADIUS IS APPROXIMATELY',
        1F10.3,'  METERS'/)
         GO TO 47
      45 PRINT 46,XO(1)
      46 FORMAT (' ',35X,'THE LOW POPULATION RADIUS IS LESS THAN',F10.3,'
        1METERS'/)
      47 CONTINUE
C
C        COMPUTE CONCENTRATIONS
C
         PRINT 48
      48 FORMAT ('1CRITICAL ISOTOPE INFORMATION'/' ',10X,'NOTE 1 -'
        1' INDICATES DISTANCE LESS THAN MINIMUM DISTANCE.'/11X,
        2'NOTE 2 - INDICATES DISTANCE GREATER THAN MAXIMUM DISTANCE.'
        3//' ISOTOPE',3X,'CURIES/MW',6X,'MPCC(UC/KG)    HALF LIFE(HRS)'
        4'   DISTANCE(M)    NOTE'/)
```

Table E-2. (continued)

```
    DO 54 K=1,NI
    IF (PCC(K).EQ.0.0) GO TO 49
    DOTM=AMT(K)*POWER*PER(K)*RATE*ALPHA*1000.0
    NOTE=0
    CONC(1)=DOTM*TERM(NV,1)
    IF (CONC(1).GE.PCC(K)) GO TO 50
    DIST(K)=XO(1)
    NOTE=1
    GO TO 52
 49 DIST(K)=0.0
    GO TO 54
 50 DO 51 N=1,NX
    CONC(N)=DOTM*TERM(NV,N)*DEXP(-0.693/HALF(K)*XO(N)/VO(NV))
    IF (CONC(N).GT.PCC(K)) GO TO 51
    IF (N.EQ.1)DIST(K)=XO(1)
    IF (N.EQ.1) GO TO 52
    DIST(K)=XO(N-1)+(CONC(N-1)-PCC(K))*(XO(N)-XO(N-1))/(CONC(N-1)-
   1CONC(N))
    GO TO 52
 51 CONTINUE
    DIST(K)=XO(NX)
    NOTE=2
 52 PRINT 53,IDENT(K),AMT(K),PCC(K),HALF(K),DIST(K),NOTE
 53 FORMAT (' ',I5,3X,4(D11.3,5X),I2)
 54 CONTINUE
    STOP
    END


    SUBROUTINE SOURCE(NI,XEM)
    IMPLICIT REAL*8(A-H,O-Z)
    COMMON/ISOT/IDENT(200),AMT(200),PCC(200),DIST(200),TIME(200)
   1/MISC/POWER,GAM(200,7),PER(200)
    DIMENSION A(200,7),SUM(7),EN(7),TEMP(7)
    DO 100 I=1,NI
    DO 100 J=1,7
    A(I,J)=AMT(I)*GAM(I,J)*PER(I)*0.01*POWER
100 CONTINUE
    DO 101 J=1,7
    SUM(J)=0.0
    DO 101 I=1,NI
    SUM(J)=SUM(J)+A(I,J)
101 CONTINUE
    EN(1)=4.30D-15
    EN(2)=1.46D-14
    EN(3)=2.04D-14
    EN(4)=3.17D-14
    EN(5)=2.05D-14
    EN(6)=4.17D-14
    EN(7)=5.26D-14
```

Table E-2. (continued)

```
        XEM=0.0
        DO 102 J=1,7
        TEMP(J)=EN(J)*SUM(J)
        XEM=XEM+TEMP(J)
    102 CONTINUE
        XEM=XEM*3.7D+10
        RETURN
        END


        SUBROUTINE LIMIT(X,V,XL,XU,IERR)
C       LIMIT ERROR MESSAGE HAS THE FOLLOWING MEANINGS:
C       -0- UPPER AND LOWER LIMIT LESS THAN 4 HRS. NO ERROR
C       -1- UNABLE TO ACHIEVE DESIRED ACCURACY ON UPPER LIMIT
C       -2- UNABLE TO ACHIEVE DESIRED ACCURACY ON LOWER LIMIT
C       -3- UNABLE TO ACHIEVE DEISRED ACCURACY ON EITHER UPPER
C           OR LOWER LIMIT
C
        IMPLICIT REAL*8(A-H,O-Z)
        IERR=0
        I=0
        IF (V.EQ.0.0) GO TO 210
        TSET=X/V
        TMAX=FCT(TSET)
        IF (V.LT.0.060) GO TO 201
        IF (V.LT.0.100) GO TO 202
        IF (V.LE.0.500) GO TO 203
        TI=0.2*TSET
        GO TO 204
    200 XU=100.0*TSET
        IF (V.GE.0.060)XU=20.0*TSET
        IF (V.GE.0.100)XU=10.0*TSET
        IF (V.GT.0.500)XU=5.0*TSET
        IERR=1
        GO TO 206
C
C       SET UPPER LIMIT
C
    201 TI=5.0*TSET
        GO TO 204
    202 TI=TSET
        GO TO 204
    203 TI=0.5*TSET
    204 T=TSET
    205 T=T+TI
        I=I+1
        IF (I.EQ.20) GO TO 200
        IF (FCT(T)/TMAX.GE.0.001) GO TO 205
        XU=T
        IF (V.GT.0.500) GO TO 208
```

Table E-2. (continued)

```
C
C       SET LOWER LIMIT
C
  206 I=0
      TL=TSET
  207 TL=TL/2.0
      I=I+1
      IF (I.EQ.20) GO TO 211
      IF (FCT(TL)/TMAX.GE.0.001) TO TO 207
      XL=TL
      GO TO 210
  208 I=0
      TL=TSET
  209 TL=0.8*TL
      I=I+1
      IF (I.EQ.20) GO TO 211
      IF (FCT(TL)/TMAX.GE.0.001) GO TO 209
      XL=TL
      GO TO 212
  210 XL=X
      XU=1.0D+6*X
      GO TO 212
  211 XL=1.0/2.0**20*TSET
      IERR=IERR+2
  212 RETURN
      END


      FUNCTION FCT(T)
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON ALPHA,BETA,AX,NX/FUN/VEL,XX
      FCT=1.0/T**1.5/DSQRT(1.0+BETA*T**2)*DEXP(-(XX-VEL*T)**2/
     1(4.0*AX*T*(1.0+BETA*T**2)))
      RETURN
      END
/*
```
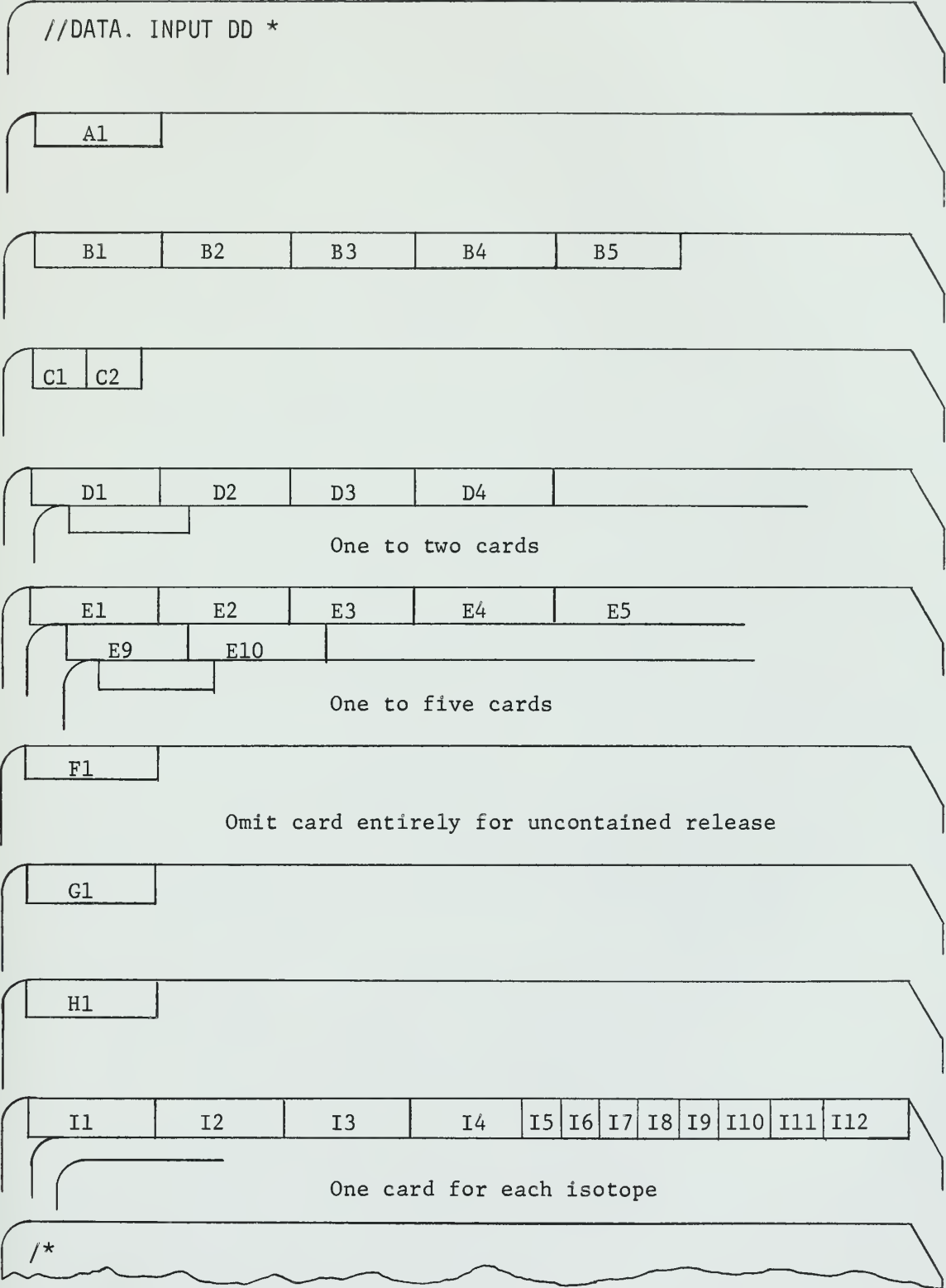
Table E-3. Data Card Information for SEADIF

CARD LOCATION	INPUT	UNITS	FORMAT	COMPUTER PROGRAM NAME	REMARKS
A1	Power	MW	F10.4	POWER	
B1	A_x	m^2/sec	F10.3	AX	
B2	A_y	m^2/sec	F10.3	AY	
B3	A_z	m^2/sec	D10.3	AZ	
B4	Ω_y	per sec	D10.3	OMEGAY	
B5	Ω_z	per sec	D10.3	OMEGAZ	
C1	Number of velocity cases	-	I3	NV	Must be from 1 to 16.
C2	Number of distances	-	I3	NX	Must be from 1 to 40.
D1 thru D16	Current Velocity	m/sec	8F10.3	VO(I)	Must be ordered beginning with smallest to largest velocity. Must be ≥ 0.
E1 thru E40	Distance from Release	meters	8F10.2	XO(I)	Must be ordered smallest to largest. Minimum distance is 5 meters. Interval between distances must not exceed 5000 m.
F1	Leak Rate	per sec	D10.3	RATE	Omit card completely for uncontained release.
G1	Containment Diameter	meters	F10.2	DIAM	This is an optional input. If used, program will incorporate virtual distance concept. If this is not desired, a blank card must be inserted at this point.

Table E-3. (continued)

CARD LOCATION	INPUT	UNITS	FORMAT	COMPUTER PROGRAM NAME	REMARKS
H1	Number of Isotopes	-	I3	NI	Must be from 1 to 200 and agree with total number of isotope information cards.
I1	Isotope Identification Number	-	I5	IDENT(I)	Isotope identification number is constructed as follows: First 2 digits: Atomic number Next 2 digits: Last digits of mass no. Fifth digit: 1 if isomer; 0 otherwise. Example: $_{38}Sr^{90} = 38900$ $_{52}Te^{121m} = 52211$
I2	M_i	curies/MW	D10.3	AMT(I)	
I3	MPCC	$\mu c/kg$	D10.3	PCC(I)	If left blank, peak concentration will not be determined.
I4	Half life	hours	D10.3	HALF(I)	
I5 thru I11	% decay by energy group	%	7F5.1	GAM(I,J)	If all spaces left blank, isotope will not be included in fission product release inventory.
I12	Solubility	-	F5.3	PER(I)	Amount of isotope released to containment. For soluble isotope PER=1.0; for insoluble isotope PER=0.01.

Figure E-1.   Data Card Layout for SEADIF

//DATA. INPUT DD *

A1

B1	B2	B3	B4	B5

C1	C2

D1	D2	D3	D4

One to two cards

E1	E2	E3	E4	E5
E9	E10

One to five cards

F1

Omit card entirely for uncontained release

G1

H1

I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12

One card for each isotope

/*